Interim Geologic Map of The Divide Quadrangle, Washington County, Utah

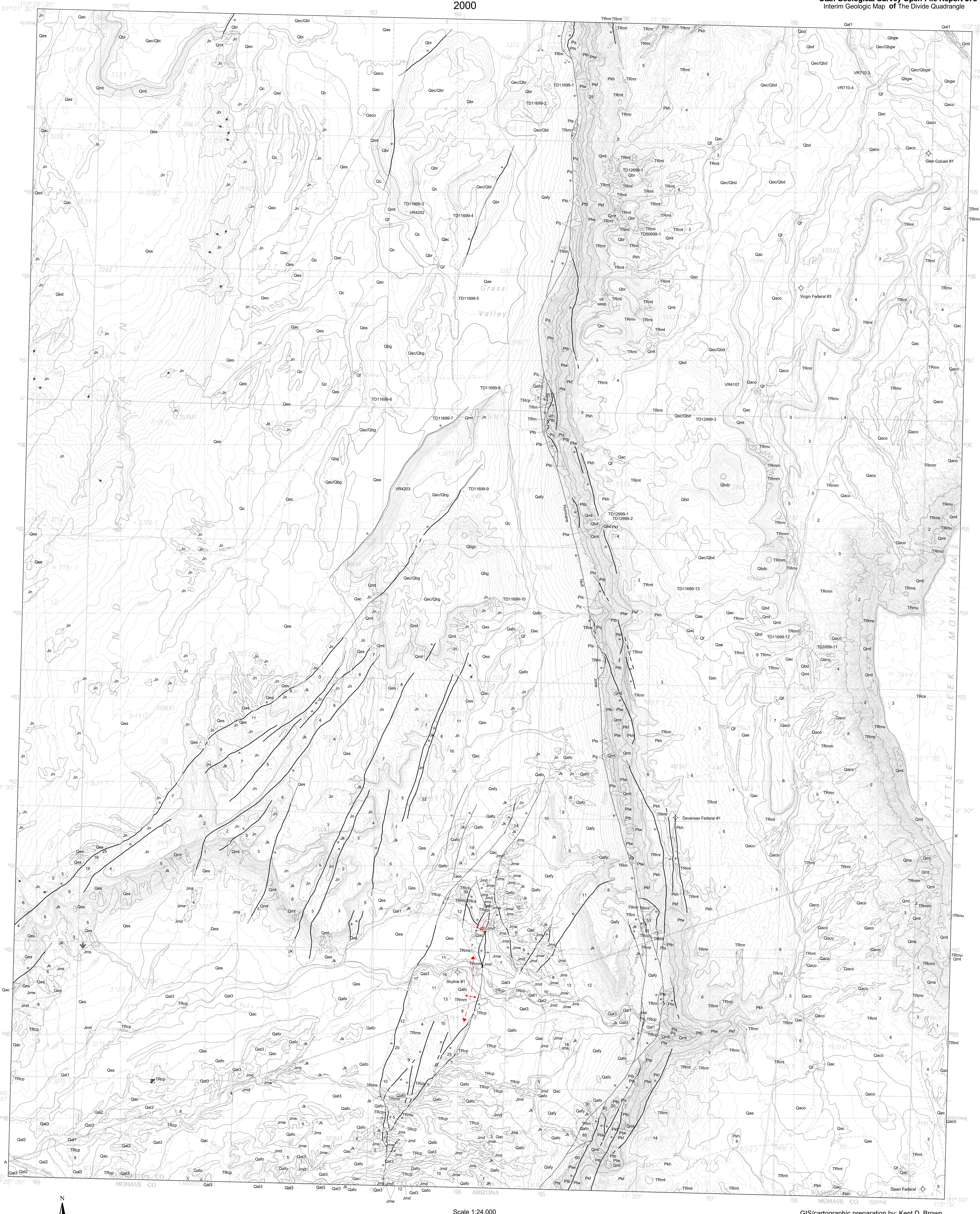
by

Janice M. Higgins,
Utah Geological Survey

2000

Utah Geological Survey
a division of
Utah Department of Natural Resources
in cooperation with
U.S. Geological Survey

Plate 1
Utah Geological Survey Open-File Report 378
Interim Geologic Map of The Divide Quadrangle



Scale 1:24,000

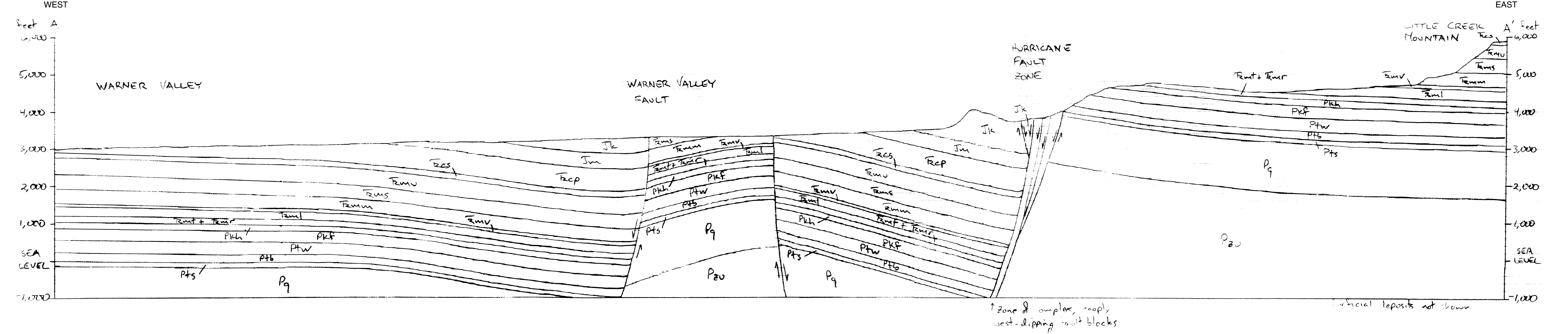
1 0 1 Miles

1 0 1 2 Kilometers

Contour Interval 20 Feet

Projection: UTM
Zone: 12
Datum: NAD 27
Spheroid: Clarke 1866

GIS/cartographic preparation by: Kent D. Brown

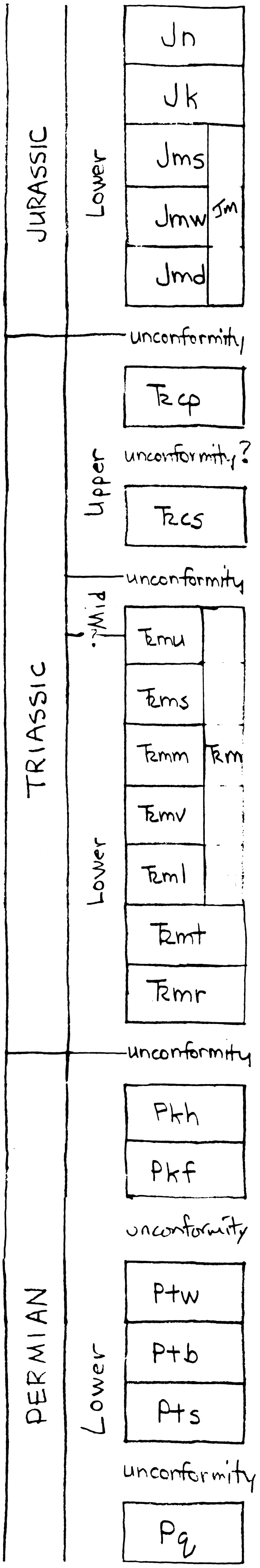


WEST
EAST
feet A
A' feet
6,000
5,000
4,000
3,000
2,000
1,000
SEA LEVEL
-1,000
WARNER VALLEY
WARNER VALLEY FAULT
HURRICANE FAULT ZONE
LITTLE CREEK MOUNTAIN
Jk
Jm
Pq
Pzu
Pts
Ptb
Ptw
Pkf
Pkh
Zone of complex, steeply west-dipping fault blocks
deposits not shown

Map symbols

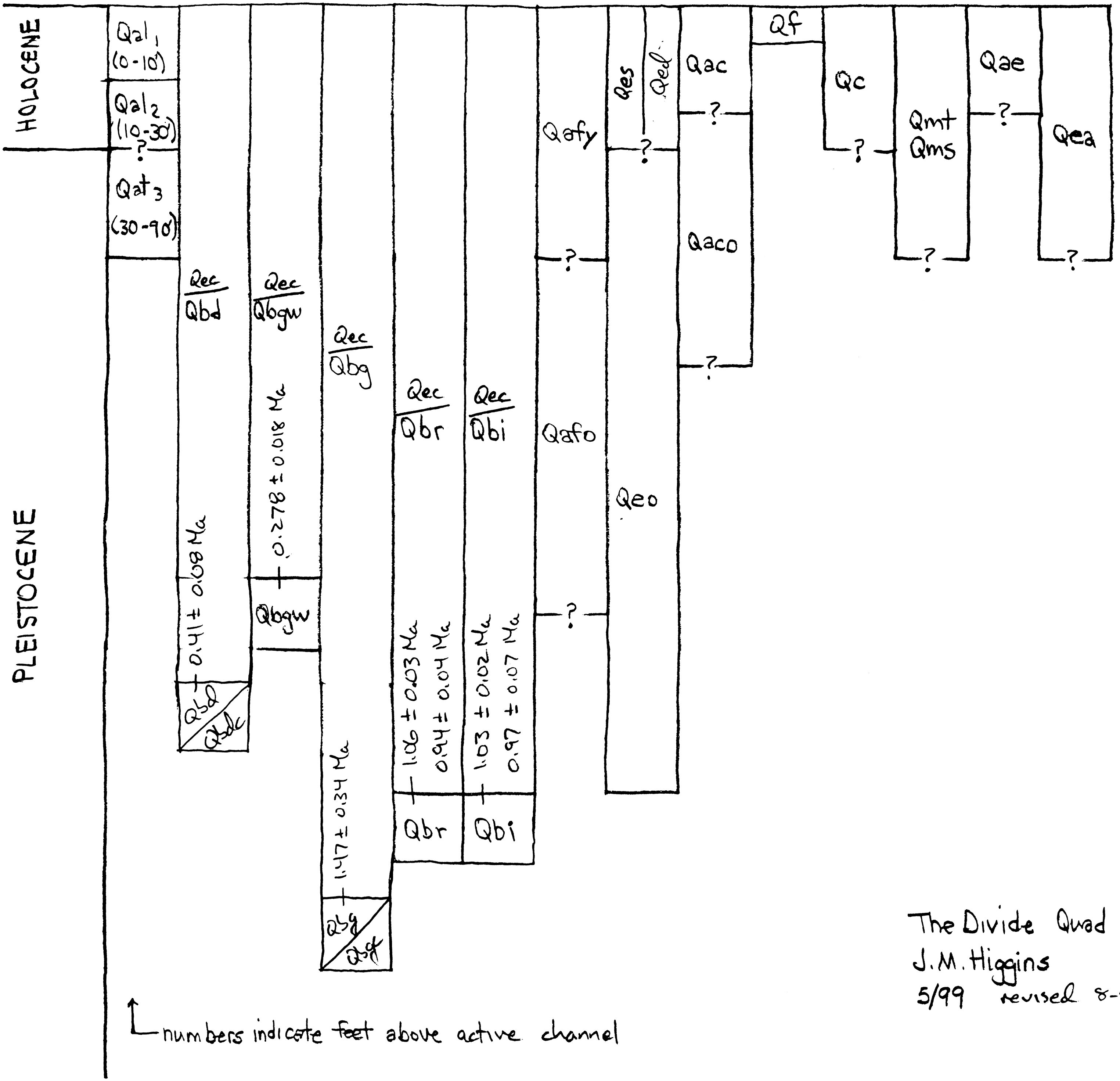
	Contact; dashed where approximate
	High-angle normal fault, dashed where approximate, dotted where concealed; bar-and-ball on down-thrown side
	Approximate trace of anticline; arrows show direction of plunge
8	Strike and dip of inclined bedding from field measurements
10	Approximate strike and dip of inclined bedding determined from photogrammetry
	Strike of vertical joint
	Sand and gravel pit
×	Uranium prospect
	Mine shaft
	Spring
oil seep	Oil seep
Dawn Federal	Oil well test hole, plugged and abandoned, with name
	Cinder cone
	Dinosaur footprints
TD12999-1	Sample location and number
A ——— A′	Line of cross section

CORRELATION OF BEDROCK UNITS



"The Divide" - J.M. Higgins 7/99

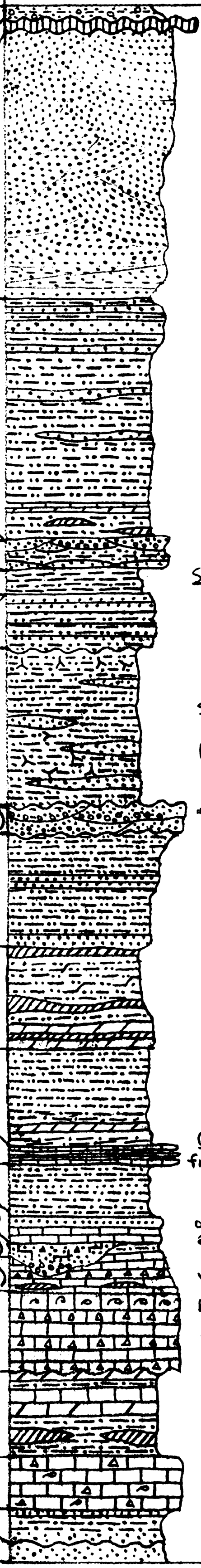
CORRELATION OF QUATERNARY UNITS



The Divide Quad
J.M. Higgins
5/99 revised 8-8-0

Stratigraphic Column - The Divide - J. M. Higgins - Plate 2

System	Series	Formation	Member	Symbol	Thickness feet (meters)	Lithology
Quaternary		Surficial deposits		Q	0-50 (0-15)	
Quaternary		Basalt flows		Qb	0-40 (0-12)	
Jurassic	Lower	Navajo Sandstone		Jn	1000+ (305+)	Sand Mountain; high-angle cross beds; Transition zone
Jurassic	Lower	Kayenta Formation		Jk	900 (273)	
Jurassic	Lower	Moenave Formation	Springdale Sandstone Member	Jms (Jm)	120 (36)	gypsum; petrified wood
Jurassic	Lower	Moenave Formation	Whitmore Point Member	Jmw (Jm)	80 (24)	*Semionotus kanabensis*
Jurassic	Lower	Moenave Formation	Dinosaur Canyon Member	Jmd (Jm)	200 (61)	
Triassic	Upper	Chinle Formation	Petrified Forest Member	TRcp	600± (185)	swelling clays; petrified wood
Triassic	Upper	Chinle Formation	Shinarump Cong Mbr	TRcs	75-165 (23-49)	"Picture stone"
Triassic	Mid.	Moenkopi Formation	Upper red Member	TRmu (TRm)	425 (129)	
Triassic	Lower	Moenkopi Formation	Shnabkaib Member	TRms (TRm)	375 (114)	
Triassic	Lower	Moenkopi Formation	Middle red member	TRmm (TRm)	360 (109)	
Triassic	Lower	Moenkopi Formation	Virgin Ls Mbr	TRmv (TRm)	75 (23)	Composite brachiopods; five sided crinoid columnals
Triassic	Lower	Moenkopi Formation	Lower red member	TRml (TRm)	200 (61)	
Triassic	Lower	Moenkopi Formation	Timpoweap Member	TRmt	50-125 (15-37)	oil seep
Triassic	Lower	Moenkopi Formation	Rock Canyon Cong. Mbr	TRmr	0-130 (0-39)	ammonites
Permian	Lower	Kaibab Formation	Harrisburg Member	Pkh	30-175 (9-53)	white chert; gypsum
Permian	Lower	Kaibab Formation	Fossil Mountain Member	Pkf	300 (91)	Brachiopods; "black-banded" chert
Permian	Lower	Toroweap Formation	Woods Ranch Member	Ptw	320 (98)	gypsum
Permian	Lower	Toroweap Formation	Brady Canyon Member	Ptb	200 (61)	brachiopods
Permian	Lower	Toroweap Formation	Seligman Mbr.	Pts	115 (36)	
Permian	Lower	Queantoweap Sandstone		Pq	75+ (23+)	



INTERIM GEOLOGIC MAP OF THE DIVIDE 7.5' QUADRANGLE, WASHINGTON COUNTY, UTAH

by
Janice M. Higgins

OPEN-FILE REPORT 378 **December 2000**
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
***in cooperation with* U.S. Geological Survey**
STATEMAP Agreement No. 99HQAG2067

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The Divide 7.5' Quadrangle,

Washington County, Utah

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Utah Geological Survey
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ABSTRACT

The Divide quadrangle in southwest Utah is bisected north-south by the Hurricane fault zone. The east half of the quadrangle is part of the Colorado Plateau while the west half is part of the transition zone that leads into the Basin and Range Province farther west. Over 1,000 feet (305 m) of Permian rocks, including the upper part of the Queantoweap Sandstone and the Toroweap and Kaibab Formations, are exposed in the Hurricane Cliffs, along the footwall of the Hurricane fault zone. The Triassic Moenkopi Formation is 1,610 feet (488 m) thick and unconformably overlies paleotopography eroded into the Kaibab Formation. It in turn is unconformably overlain by the Chinle Formation, which is 700 feet (212 m) thick. This Triassic section forms Little Creek Mountain along the east edge of the quadrangle; it is also partially exposed in Warner Valley in the southwest portion of the quadrangle and as a dome within a pod-shaped horst created by the Warner Valley fault. Slivers of Triassic rocks are also caught in the Hurricane fault zone. A Jurassic section consisting of the Moenave Formation, 400 feet (121 m) thick; the Kayenta Formation, 900 feet (273 m) thick; and the basal 1,000 feet (305 m) of the Navajo Sandstone, is exposed in the quadrangle. The Moenave Formation is repeated several times in Warner Valley due to faulting, while the Kayenta Formation and Navajo Sandstone form Sand Mountain in the northwest part of the quadrangle.

Five Quaternary basaltic flows are in the quadrangle. Two flows lie west of the Hurricane fault (Ivan's Knoll and Grass Valley), and two flows lie east of the fault (Gould Wash and The Divide). The Remnants flow straddles, and is offset by, the fault. Because of continued erosion, the older flows now cap ridges, forming inverted valleys. Relative uplift and downcutting west and east of the fault are also documented by alluvial-terrace deposits and other elevated alluvial surfaces capped by thick pedogenic carbonate.

Many normal faults displace the rocks in The Divide quadrangle, but only three have more than a few tens of feet of displacement. The largest of these three is the down-to-the-west Hurricane fault zone which has about 5,000 feet (1,515 m) of displacement near the south end of the quadrangle, much of which has occurred during Quaternary time. Displacement across the Hurricane fault zone increases northward to at least 6,000 feet (1,818 m) near the north end of the quadrangle. Farther west, the Warner Valley fault, with about 1,800 feet (545 m) of displacement, cuts Quaternary deposits.

Geologic resources in The Divide quadrangle include gravel from alluvial fan deposits, sand, and stone. There has also been exploration for gypsum, petroleum, uranium, and paleoplacer deposits of precious metals in the quadrangle. Water resources are increasingly important as population growth in the area continues. Flooding; slope failures, including rock falls and landslides; expandable, soluble, and collapsible rock and soil; blowing sand; earthquakes; volcanic eruptions; and radon gas are of concern as development continues.

CONTENTS

INTRODUCTION

The Divide quadrangle is located in south-central Washington County in the southwest corner of Utah (figure 1). This area, nicknamed "Utah's Dixie," is one of the fastest growing areas in the state and many geologic concerns are arising as the population increases. Water supplies are limited and must be protected from contamination and misuse. Construction materials, particularly gravel, are in short supply. Expansive, soluable, and collapsible soil and rock – which can adversely affect buildings, roads, and other structures – are present and need to be recognized by planners and builders. Other potential geologic hazards include earthquakes, blowing sand, flooding, debris flows, mass movements, radon gas, and volcanoes.

[figure 1 near here]

Maximum topographic relief is just over 2,932 feet (888 m) from the top of Little Creek Mountain at 5,912 feet (1792 m) above sea level to the northwest corner of the quadrangle where Sand Hollow Reservoir will inundate a portion of Sand Mountain at about 2,980 feet (903 m). The Permian rocks of the Hurricane Cliffs create a formidable barrier that trends north-south, bisecting the quadrangle. To the east of these cliffs, a normal stratigraphic sequence of Triassic Moenkopi Formation sits on top of this Permian section. This formation makes up Little Creek Mountain, which is capped by the Shinarump Conglomerate Member of the Chinle Formation. The stratigraphic column picks up again west of the Hurricane Cliffs where the less-resistant Petrified Forest Member of the Chinle Formation and the Jurassic Moenave Formation create Warner Valley along the south edge of the quadrangle. North of Warner Valley is Sand Mountain, formed by the Kayenta Formation and the basal part of the Navajo Sandstone. These strata create two steps on the "Grand Staircase" of rock (Gregory, 1950) that stretches across southern Utah and northern Arizona: the Triassic Chocolate Cliffs, capped by the Shinarump Conglomerate Member of the Chinle Formation, and the Jurassic Vermillion Cliffs, capped by the Kayenta Formation and the lower Navajo Sandstone. However, in The Divide quadrangle, this staircase is displaced by the Hurricane fault, making the younger Vermillion Cliffs of Sand Mountain lower in elevation than the older Chocolate Cliffs of Little Creek Mountain.

The Virgin River lowland that includes The Divide quadrangle has the lowest elevation, warmest climate, and the longest growing season in Utah. It receives about 8 inches (20 cm) of precipitation annually (Cordova and others, 1972). Natural vegetation includes sparse grasses, sagebrush, creosote bush, and several varieties of cactus and yucca.

The U.S. Army Topographical Survey and U.S. Geological Survey investigated southwest Utah geology during the latter half of the 19th century (Powell, 1875; Dutton, 1882). Dobbin (1939) produced a small-scale geologic map of the greater St. George area that focused on structural geology. Gardner's (1941) report of the Hurricane fault zone in southwestern Utah and northwestern Arizona included a 1:320,000-scale geologic map. Gregory (1950) mapped the Zion Canyon area to the east (1:125,000) and established many of the geologic names in use today. Marshall (1956a, b) made photogeologic maps of the Little Creek Mountain quadrangle to the east and the Virgin quadrangle to the northeast, both at a scale of 1:24,000. Cook (1960) completed a map of Washington County at a scale of 1:125,000 which is still the most detailed map available for parts of the county. Eppinger and others (1990) compiled a 1:250,000-scale map of the Cedar City 1°x 2° quadrangle, which includes The Divide quadrangle. Billingsley (1992a, b) mapped the Yellowhorse Flat and Rock Canyon quadrangles in Arizona, southwest and south of The Divide quadrangle, at a scale of 1:24,000. Higgins (1998) mapped the Washington Dome quadrangle to the west at a scale of 1:24,000. Biek (1997, 1998) mapped the Harrisburg Junction quadrangle to the northwest and the Hurricane quadrangle to the north, both at a scale of 1:24,000. Many topical studies have been done on structure, stratigraphy, volcanism, hazards, and economic and water resources of the area.

DESCRIPTION OF MAP UNITS

The oldest rocks in The Divide quadrangle are the Early Permian Queantoweap Sandstone, Toroweap Formation, and Early Permian Kaibab Formation. They form the Hurricane Cliffs that trend north-south through the quadrangle (figure 2). The area east of these cliffs is comprised of a complete section of the Early Triassic Moenkopi Formation that forms Little Creek Mountain, which is capped by the Shinarump Conglomerate Member of the Late Triassic Chinle Formation. With the exception of the Petrified Forest Member of the Chinle Formation, which forms most of Warner Valley, and the pod-shaped horst of Triassic rocks in east Warner Valley, all exposed sedimentary rocks west of the Hurricane Cliffs are Jurassic in age. This section includes the Early Jurassic Moenave Formation, which is repeated several times by faulting in Warner Valley, and the Kayenta Formation and Navajo Sandstone, which form Sand Mountain.

[Figure 2 near here]

Five Quaternary basaltic lava flows or groups of flows cover part of the north half of the quadrangle. Ivan's Knoll and Gould Wash flows are derived from cinder cones just north and just east of the quadrangle, respectively. The cinder cone for the Grass Valley flow and two cinder cones for The Divide flow are well preserved within the quadrangle. The Remnants flow, which is contained completely within the quadrangle, no longer has a well-formed cinder cone; however, it was probably immediately east of the Hurricane fault between the "Three Brothers," which are the northern three of the five hills capped by this flow. The portion of the flow on the up-thrown side is extensively eroded and the probable cinder cone mostly destroyed while the portion of the flow on the down-thrown side has been somewhat eroded, but mostly buried by alluvial-fan deposits near the fault. This flow thus clearly demonstrates that downcutting rates are largely a function of the amount and rate of relative uplift. The immediate area is famous for classic examples of inverted topography (Hamblin, 1963, 1987) where erosion removes adjacent, less resistant strata, leaving the resistant flow standing as a high linear ridge. The amount of inversion has been used to give relative ages of different flow complexes, but caution should be used when trying to so correlate flows on different structural blocks. Continued erosion of even the down-thrown block is confirmed by three main levels of gravel terraces and older alluvial-fan deposits. Thin alluvial, colluvial, eolian, and mass movement deposits cover much of the quadrangle.

Permian and Mesozoic strata in the quadrangle were deposited in shallow-marine to low-level terrestrial environments and lithologies strongly reflect sea-level fluctuations (figure 3). Vail and others (1977), Mitchum (1977), and Van Wagoner and others (1990) recognized major cycles in the depositional record that are divisible into first-order megasequences through fifth-order parasequences, according to duration and extent of the cycle. Permian rocks exposed in the quadrangle were deposited near the end of the Paleozoic megasequence and the Triassic rocks mark the beginning of the Mesozoic/Cenozoic megasequence. A Permian lowstand near the end of the Paleozoic megasequence exposed the Kaibab Formation to erosion. After the lowstand, sea level rose to near the record high where it fluctuated but remained high until the Early Jurassic, when it dropped to about 500 feet (150 m) below present sea level (Vail and others, 1977). These fluctuations in sea level define eight supercycles (second-order sequences) (Van Wagoner and others, 1990). However, only five of the eight are documented in rocks in the quadrangle.

[figure 3 near here]

Permian

The Permian rock exposed in the quadrangle includes the upper portion of the Queantoweap Sandstone, the Toroweap Formation, and the Kaibab Formation. Outcrops of these units are confined to the Hurricane Cliffs, which were created by displacement and differential erosion along the Hurricane fault. These rocks make up two second-order cycles at the end of the Paleozoic first-order megasequence. The Queantoweap Sandstone represents the highstand systems tract of a third-order cycle within the older of these two second-order cycles. The Toroweap and Kaibab Formations constitute the other second-order cycle with each formation being a third-order cycle (figure 3).

The Kaibab Formation represents only the highstand systems tract of the younger third-order cycle of the final second-order cycle that began in the Early Permian (figure 3). A subsequent Late Permian lowstand resulted in subaerial exposure and extensive erosion of the Kaibab Formation, which completely removed the Harrisburg Member and cut deeply into the Fossil Mountain Member in areas farther west (Jenson, 1984; Higgins, 1997). In The Divide quadrangle, the Harrisburg Member thins but is not completely removed. The Kaibab Formation is late Early Permian (Leonardian) in age (McKee, 1938; Rawson and Turner-Peterson, 1979; Sorauf and Billingsley, 1991).

Queantoweap Sandstone (Pq)

The package of clastic rocks usually considered as the Queantoweap Sandstone in Utah (Hintze, 1986a, b; Higgins, 1997) continue farther south into northwest Arizona and southeastern Nevada where the lower portion has been called either the Queantoweap Sandstone or the Esplanade Sandstone and the upper portion the Hermit Formation, Hermit Shale (McNair, 1951; McKee, 1975, 1982; and Rowland, 1987), or the Coconino(?) Sandstone (McKee, 1934). On the geologic map of the Rock Canyon quadrangle that adjoins this study area to the south, Billingsley (1992b) called the upper 760 to 800 feet (230-245 m) of red and white, ledge- and slope-forming sandstone and siltstone the sandstone facies of the Hermit Shale. In his stratigraphic study of the area, Billingsley (1997) submits that since the clastic sequence apparently becomes a white, low-angle, cross-bedded sandstone in southwestern Utah, the entire sequence in The Divide quadrangle should be mapped as Queantoweap Sandstone. Only the upper 75 feet (23 m) is exposed within the quadrangle as a pale-yellow to grayish-pink, calcareous, thick-bedded, fine-grained sandstone that forms a steeply dipping, ledgy-slope at the base of a portion of the Hurricane Cliffs. The Queantoweap Sandstone is Early Permian (Wolfcampanian) in age and was deposited in a shallow-marine environment (Billingsley, 1997). The unconformable upper contact is placed at the break in slope that signifies the base of the Seligman Member of the Toroweap Formation.

Toroweap Formation

The Early Permian Toroweap Formation, which consists of sediment deposited during shallow sea regression, transgression, and subsequent regression (Rawson and Turner-Peterson, 1979; Sorauf and Billingsley, 1991), is exposed only along the Hurricane Cliffs. It is mapped using nomenclature defined by Nielson (1981, 1986) that divides the formation into three members: Seligman Member, Brady Canyon Member, and Woods Ranch Member.

Seligman Member (Pts): The Seligman Member forms a poorly exposed slope in the face of the Hurricane Cliffs. It consists of a basal part of pale-yellowish-brown, fine-grained sandstone; a middle part of interbedded yellowish-gray, calcareous, very-fine-grained sandstone and grayish-yellow, gypsiferous, calcareous siltstone; and an upper part of medium-gray, thin-bedded, sandy limestone. The Seligman Member is 115 feet (36 m) thick near the south edge of the quadrangle. Biek (1998) estimated a thickness of 30 to 50 feet (9-15 m) to the north and Billingsley (1992b) reported a thickness of 100 to 200 feet (30-60 m) to the south along the Hurricane Cliffs.

Brady Canyon Member (Ptb): The Brady Canyon Member consists of medium-light-gray to dark-gray, medium- to course-grained, thick-bedded, fossiliferous limestone with reddish-brown, rounded chert nodules. Slightly dolomitic near its base and top, the limestone contains abundant poorly preserved crinoid stems and disarticulated brachiopods, as well as coral and sponge fragments. It forms the prominent, lower cliff along the Hurricane Cliffs and is 200 feet (61 m) thick. The upper unconformable contact is placed at the top of the massive cliff where the gypsiferous slope of the Woods Ranch Member begins.

Woods Ranch Member (Ptw): The slope-forming Woods Ranch Member is commonly covered with talus. It is grayish-pink to very-pale-orange massive gypsum with interbeds of light-brownish-gray siltstone, pale-red shale, and yellowish-gray to light-gray, laminated to thin-bedded dolomite and limestone. The bedding is distorted from dissolution of gypsum. This member is 320 feet (98 m) thick. The upper contact with the Fossil Mountain Member of the Kaibab Formation is unconformable and channel erosion into the Woods Ranch Member produced local relief of as much as 12 feet (3 m). The contact is drawn at the base of the massive cliff of the overlying Fossil Mountain Member of the Kaibab Formation.

Kaibab Formation

The Early Permian Kaibab Formation consists of sediment deposited by a transgressive, then regressive shallow sea (McKee, 1938; Rawson and Turner-Peterson, 1979; Nielson, 1981). It is divided into two members after Nielson (1981) and Sorauf and Billingsley (1991): the Fossil Mountain Member and the Harrisburg Member.

Fossil Mountain Member (Pkf): The Fossil Mountain Member forms the upper prominent limestone cliff of the Hurricane Cliffs. It consists of yellowish-gray, abundantly fossiliferous, cherty limestone that contains silicified fossils, including corals, brachiopods, crinoids, and bryozoans. The outcrop often appears black banded because of reddish-brown and black chert that forms irregularly bedded nodules. Total thickness is 300 feet (91 m). The upper contact with the Harrisburg Member is conformable and is drawn at the base of the first thick gypsum bed, just above the top of the massive cliff.

Harrisburg Member (Pkh): The Harrisburg Member, named for a type section at Harrisburg Dome just northwest of the study area (Reeside and Bassler, 1921; Sorauf, 1962), is exposed near the top of the Hurricane Cliffs. Since Sorauf's type section is incomplete, Nielson (1981, 1986) established two reference sections that illustrate the rapid east-west facies changes of the Harrisburg Member. One section, west of the quadrangle in Mountain Valley Wash, is typical of western exposures (figure 1). A second section, located north of the quadrangle in Timpoweap Canyon, is typical of eastern facies along the Hurricane Cliffs, including those of The Divide quadrangle. In The Divide quadrangle, the Harrisburg Member is light-gray, fossiliferous, sandy, fine- to medium-grained limestone interbedded with red and gray gypsiferous siltstone and sandstone, and gray gypsum beds several feet thick. Dissolution of interbedded gypsum has locally distorted the member. It forms a slope with limestone ledges. Beds of cherty limestone, sandy limestone, and chert, informally referred to as the "medial limestone" (Nielson, 1981), form a resistant low cliff about 30 feet (9 m) high near the middle of the member.

Several hundred feet of post-depositional, subaerial erosion during Late Permian and Early Triassic time completely removed the Harrisburg Member from the southwest part of the Price City Hills in the Bloomington dome portion of the Virgin anticline (Higgins and Willis, 1995). In the Beaver Dam Mountains to the west, Jenson (1984) and Higgins (1997) describe karst topography with more than 500 feet (152 m) of relief that formed during this 15-million-year period of erosion (Nielson, 1981; Sorauf and Billingsley, 1991). In The Divide quadrangle, only part of the Harrisburg Member is removed. Channels, some as deep as 170 feet (52 m), are filled with the Rock Canyon Conglomerate Member of the Moenkopi Formation and younger strata. Elsewhere, the Harrisburg Member is overlain by the Timpoweap Member of the Moenkopi Formation (figure 4). The upper contact, which is poorly exposed, highly variable, and unconformable, is locally difficult to follow where Rock Canyon strata are not well developed.

[Figure 4 near here]

Thickness of the Harrisburg Member varies from 30 to 175 feet (9-53 m) in the quadrangle. Nielson (1981) measured 280 feet (85 m) near the southwest end of the Price City Hills in Bloomington dome and an incomplete section of 185 feet (56 m) near the northeast end of Bloomington dome, to the southwest. Biek (1997) described an incomplete section 250 feet (75 m) thick at Harrisburg Dome to the northeast, and a varying thickness from 100 to 160 feet (30-49 m) just to the north in the Hurricane quadrangle (Biek, 1998).

Triassic

The Lower Triassic Moenkopi and Upper Triassic Chinle Formations are separated by an unconformity of about ten million years (figure 3). These formations denote two major second-order supercycles of Vail and others (1977) separated by a smaller rise and subsequent fall of sea level during middle Triassic time (Paull and Paull, 1994).

[Figure 5 near here]

Moenkopi Formation

The Moenkopi Formation is divided into seven members after Reeside and Bassler (1921) and Stewart and others (1972b) with a total thickness of about 1,700 feet (715 m) in The Divide quadrangle. This formation is Early to Middle Triassic in age (late Scythian to early Anisian) (Dubiel, 1994).

The Moenkopi Formation was deposited on a very gentle slope where sea level changes of several feet translated into shoreline changes of tens of miles. It represents a second-order supercycle that can be subdivided into three distinct third-order sequences depicting smaller transgressive-regressive cycles in an overall sea level rise (figures 3 and 5). Paull & Paull (1994) stated that the Early Triassic global rise in sea level from the Permian lowstand was greater than 660 feet (200 m). Only the lowest of the three third-order sequences includes a lowstand systems tract that is documented within the quadrangle (represented by the Rock Canyon Conglomerate). Above the Rock Canyon Conglomerate is the transgressive systems tract of the Timpoweap Member, which Dubiel (1994) correlated to the Smithian-age transgression that flooded this area from the northwest. It is overlain by the highstand systems tract of the lower red member, correlated to Smithian-Spathian age regression of Dubiel (1994), which completes the lowest third-order sequence. The Virgin Limestone Member and the middle red member, respectively make up the transgressive and highstand systems tracts of the middle third-order sequence, whereas the Shnabkaib Member and the upper red member form similar systems tracts for the top third-order sequence in the Moenkopi Formation. These upper two third-order sequences are correlated to the early and late Spathian transgressions and regressions of Dubiel (1994). Paleogeographic maps and time-rock stratigraphy charts in Blakey and others (1993) and Paull & Paull (1994) depict these changes.

Rock Canyon Conglomerate (TRmr): Although Nielson (1991) proposed that this member be elevated to formation status, Hintze (1993) and other subsequent authors still treat it as a member of the Moenkopi Formation. The Rock Canyon Conglomerate fills paleocanyons eroded into the Kaibab Formation. Along much of the contact, the channel conglomerate is not present and the

Harrisburg Member of the Kaibab Formation is separated from the Timpoweap Member of the Moenkopi Formation by a thin, angular breccia that is up to 10 feet (3 m) thick in some areas.

The Rock Canyon Conglomerate Member is composed of yellowish-gray to light-olive-gray, poorly to moderately sorted conglomerate with angular to subrounded clasts. Thick beds, some of which are lenticular and indurated, form a cliff with a rough, angular surface. The basal layers include limestone rip-up clasts and blocks eroded from the Harrisburg Member as large as 14 inches (35 cm) in diameter that have been healed with sparry calcite during several episodes. Rounding in the conglomerate varies from mostly angular in the lower part to sub-angular to sub-rounded toward the top. Clasts are pebble- to cobble-size and composed primarily of chert weathered from the Kaibab Formation. The conglomerate is mostly clast supported but where matrix supported, the matrix is commonly limestone and locally coarse-grained sandstone. The Rock Canyon Conglomerate grades upward into calcareous, gritty, pebble conglomerate that is poorly sorted and includes some sandstone and some yellowish-gray, sandy limestone lenses. The upper contact is conformable where exposed and is gradational with dark-yellowish-orange to light-pinkish-gray, gritty siltstone beds of the Timpoweap Member. Thickness varies from 0 to 130 feet (0-39 m).

Timpoweap Member (TRmt): The Timpoweap Member is extensively exposed capping the Hurricane Cliffs and down the dip-slope to the east. The member was named by Gregory in 1950 for Timpoweap canyon just north of the quadrangle, but the type sections northeast of the quadrangle were not designated until 1979 by Nielson and Johnson. The Timpoweap Member forms a coherent ledge or low cliff on top of the undulating and eroded beds of the Harrisburg Member or locally above the channel-fill conglomerate or breccia of the Rock Canyon Conglomerate Member.

The lower part of the Timpoweap Member is light-gray to grayish-orange, thin- to thick-bedded limestone and cherty limestone that weathers light-brown, commonly with a merange-like surface due to protruding blebs of chert. Ammonites, gastropods, and brachiopods were all collected from these lower beds. Locally, euhedral pyrite crystals up to 1/4 inch (1 cm) across are also found. The upper part of the member is grayish-orange, thin- to thick-bedded, slightly calcareous, very fine-grained sandstone with thin-bedded siltstone and mudstone intervals that weathers yellowish-brown. An oil seep is mapped in these beds at the top of the Hurricane Cliffs just west of “White Face” and “The Wart,” which are the two southernmost hills capped by the Remnants flow in the center of the N1/2, section 34, T. 42 S., R. 13 W. Other oil seeps are known in the area (Blakey, 1979; Biek, 1998). The upper contact with the lower red member is gradational and conformable and is drawn at the top of the highest yellowish-brown siltstone, sandstone, and limestone interval beneath the reddish-brown siltstone and mudstone. This contact is covered by Quaternary alluvial deposits across most of the quadrangle and is well exposed in only a few draws around the hills capped by the Remnants flow. The Timpoweap Member varies from about 50 to 125 feet (15-37 m) thick.

Lower red member (TRml): The lower red member consists of interbedded siltstone, mudstone, and sandstone that form a slope beneath the more resistant ledges of the Virgin Limestone Member. It is generally well exposed except for the lower contact. The siltstone and mudstone are moderate-reddish-brown, generally calcareous, commonly ripple marked, and exhibit small-scale cross-bedding. Thin siltstone and mudstone beds are both interbedded with and crossed by stringers and thin veinlets of gypsum. The sandstone is reddish-brown, calcareous, very fine grained, and thinly bedded. The upper contact with the Virgin Limestone Member is placed at the base of the lowest limestone ledge. The lower red member is about 200 feet (61 m) thick in the quadrangle.

<u>Virgin Limestone Member (TRmv)</u>: The Virgin Limestone Member forms a prominent bench along the flank of Little Creek Mountain on the east edge of the quadrangle. It consists of three distinct, resistant, medium-gray to yellowish-brown, marine limestone ledges, each 5 to 10 feet (1.5-3 m) thick, except in SE1/4SE1/4 section 14, T. 43 S., R. 13 W. where the lower limestone reaches a thickness of 40 feet (12 m). These limestones are interbedded with nonresistant, moderate-yellowish-brown, muddy siltstone and pale-reddish-brown sandstone, as well as light-gray to grayish-orange-pink gypsum. The limestone ledges contain five-sided crinoid columnals. *Composita* brachiopods (Billingsley, 1992a) are found in the upper portion of the lowest limestone bed. They seem especially common where the ledge thickens.

The Virgin Limestone Member is generally 75 feet (23 m) thick, except where the lower limestone thickens. The upper contact with the middle red member is drawn at the top of the highest limestone ledge.

<u>Middle red member (TRmm)</u>: The middle red member forms a slope at the base of Little Creek Mountain, and is also exposed in a horst west of the Hurricane fault zone in the south-central part of the quadrangle. It is composed of interbedded, moderate-red to moderate-reddish-brown siltstone, mudstone, and very fine-grained, thin-bedded sandstone. Very thin interbeds and veinlets of gypsum that vary in color from greenish-gray to white are locally common. Several ledge forming gypsum beds are present near the base. The upper contact is placed where the moderate-red siltstone of the middle red member gives way to predominantly light-gray, unfossiliferous, dolomitic limestone beds that mark the base of the Shnabkaib Member. This member is 360 feet (109 m) thick.

<u>Shnabkaib Member (TRms)</u>: The Shnabkaib Member is extensively exposed about midway up the slope of Little Creek Mountain, and is also exposed in a horst west of the Hurricane fault zone in the south-central part of the quadrangle. It consists of light-gray to pale-red gypsiferous siltstone with several thin interbeds of unfossiliferous, dolomitic limestone near the base. The alternating resistant and nonresistant beds form ledge-slope topography and make the lower portion slightly more resistant to erosion than the upper portion. The gypsiferous upper portion weathers into a powdery soil and generally forms a valley except where it is held up by more resistant overlying units. Alternating light and dark colors give this member a "bacon-striped" appearance that shows up especially well on aerial photographs. The upper contact is gradational and is drawn where the greenish-gray, gypsiferous siltstone of the Shnabkaib Member grades into reddish-brown mudstone of the upper red member. This member is 375 feet (114 m) thick.

<u>Upper red member (TRmu)</u>: The upper red member of the Moenkopi Formation is well exposed, although portions of it are covered with talus. It forms a steep slope with at least one prominent sandstone ledge beneath the resistant ledge of the Shinarump Conglomerate Member of the Chinle Formation, which caps Little Creek Mountain; it is also exposed in the horst west of the Hurricane fault. The upper red member consists of moderate-reddish-brown, thin-bedded siltstone and very fine-grained sandstone with some thin gypsum beds and abundant discordant gypsum stringers. Ripple marks are common in the siltstone. The upper contact is unconformable, representing approximately 10 million years of middle Triassic time (Dubiel, 1994), and is mapped at the base of the first coarse-grained, thick-bedded, pale-yellowish-brown conglomeratic sandstone caprock that fills shallow paleovalleys eroded into the upper red member. It is estimated to be 425 feet (129 m) thick.

Moenkopi Formation, undivided (Trm): Numerous fault blocks along the Hurricane fault zone contain steeply west-dipping Moenkopi strata. These Moenkopi beds remain undivided due to structural complexity.

Chinle Formation

In The Divide quadrangle, the Chinle Formation consists of the Shinarump Conglomerate and the Petrified Forest Members. The Chinle Formation averages 725 feet (220 m) thick, but varies mostly due to changes in thickness of the basal Shinarump Member. It is Late Triassic in age (Stewart and others, 1972a) based primarily on vertebrate and plant remains. Dubiel (1994) assigned it to the early Carnian to late Norian with an unconformity of several million years separating the two members.

The Chinle Formation represents the last Triassic second-order supercycle (figure 3) (Vail and others, 1977) and can be subdivided into two distinct third-order cycles. The lower third-order cycle consists of the Shinarump Conglomerate Member, whose source was the ancestral Uncompahgre highlands to the east and a magmatic arc near the continental margin to the southwest (Blakey and others, 1993). The basal Shinarump was deposited in the lowest parts of paleovalleys cut into the upper red member of the Moenkopi Formation (Dubiel, 1994) and signifies the beginning of base level rise. The Shinarump grades upward from massive conglomerate and tabular-planar stratified sandstone to medium-grained, trough cross-stratified sandstone (a highstand systems tract) formed by hinterland braided-stream deposits. The Petrified Forest Member is the highstand systems tract of another third-order cycle. The Petrified Forest Member's fluvial systems mimicked paleoflow in the lower Shinarump system except that these stream deposits were of much higher sinuosity as evidenced by ample floodplain mudstone (Dubiel, 1994). Abundant bentonitic mudstone in the Petrified Forest Member indicates that volcanic ash formed a significant component of the sediment supply, most of which was derived from the magmatic arc at the continental margin to the southwest (Blakey and others, 1993).

Shinarump Conglomerate Member (TRcs): The Shinarump Conglomerate is very resistant and forms the moderate-brown, chert-pebble conglomerate grading to a grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone that caps Little Creek Mountain. It weathers dark brown to moderate yellowish brown. It is mostly thick to very thick bedded with both planar and low-angle cross-stratification, although thin, platy beds do occur locally. In some areas, the more coarsely grained sandstone contains fragments of poorly preserved petrified wood that is commonly replaced in part by iron-manganese oxides. Locally, the finer grained sandstone has well-developed Liesegang bands of limonite that give rise to the nicknames of "picture rock" or "landscape stone" (Bugden, 1993).

The Shinarump Conglomerate Member varies from 75 to 165 feet (23-50 m) thick in The Divide quadrangle because it backfills paleotopography and was deposited in braided-stream channels. The upper contact is unconformable (Dubiel, 1994) and is placed at the base of the first variegated, bentonitic shale of the Petrified Forest Member and, unlike areas to the northwest (Biek, 1997, 1998) and west (Willis and Higgins,1996), seems quite straight forward.

Petrified Forest Member (TRcp): The Petrified Forest Member of the Chinle Formation underlies most of Warner Valley. It consists of light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several lenticular interbeds of pale-yellowish-brown, cross-bedded, thick-bedded, resistant sandstone up to 10 feet (3 m) thick. Shaly beds weather to a "popcorn" surface due to swelling and shrinking of bentonitic clay. These swelling clays are responsible for many foundation problems in the region and form the slip plane for numerous rotational slumps. Petrified wood, often well silicified and brightly colored, is common. Although the member is usually covered by Quaternary deposits, it is well exposed where it is protected from erosion by older alluvial deposits. The upper contact is placed at the top of the highest purplish-gray shale and below reddish-brown siltstone of the Dinosaur Canyon Member of the Moenave Formation. This contact is unconformable and represents a gap of about ten million years (Dubiel, 1994). Within the quadrangle, the member is about 600 feet (185 m) thick as estimated from map relationships, but it is only 400 feet (121 m) thick to the north in the adjacent Hurricane quadrangle (Stewart and others, 1972a).

Jurassic

Three Early Jurassic formations of Sinemurian, Pliensbachian, and Toarcian age are present in the quadrangle: Moenave, Kayenta and Navajo Formations. They form the youngest second-order supercycle in The Divide quadrangle, and were deposited after sea level dropped dramatically from somewhat higher, to 500 feet (150 m) lower, than current sea level (figure 3) (Vail and others, 1977). There is no evidence of a relatively small second-order base level rise commonly placed by sequence stratigraphers in the Late Triassic to earliest Jurassic in The Divide quadrangle because Hettangian age rocks are not present (figure 3).

The Early Jurassic rocks can be further divided into two and possibly three third-order sequences. The lowest one is comprised of the three members of the Moenave Formation. The Dinosaur Canyon Member is the transgressive systems tract, the Whitmore Point Member represents the maximum flooding stage, and the Springdale Sandstone Member comprises the highstand systems tract. The middle third-order sequence is represented by the Kayenta Formation. The lower portion of the Kayenta is the transgressive systems tract with freshwater dolomite beds designated as the maximum flooding stage; the upper portion forms the highstand systems tract. The strata above a possible unconformity in the basal section of the Navajo Sandstone, perhaps at the top of an eolian tongue within fluvial sediments, may be the highstand systems tract of another third-order sequence.

Moenave Formation

Miller and others (1989) assigned this formation to the Lower Jurassic rather than the Upper Triassic largely because of the presence of fish scales from the holostean fish, *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950). The fish fossils were originally thought to be restricted to the Triassic and so conflicted with palynomorphs from the Whitmore Point Member that indicate the unit is Early Jurassic (Peterson and others, 1977; Imlay, 1980). Olsen and Padian (1986) later found that *Semionotus kanabensis* is not age diagnostic, which resolved the long-standing debate on the age of the Early Jurassic Moenave, Kayenta, and Navajo Formations. The Moenave Formation is divided into three members. The lower Dinosaur Canyon and Whitmore Point Members are Sinemurian in age whereas the upper Springdale Sandstone Member is early Pliensbachian. The formation is 400 feet (121 m) thick.

Dinosaur Canyon Member (Jmd): A complete section of the Dinosaur Canyon Member is exposed in several areas of Warner Valley. It is comprised of interbedded, ledge- and slope-forming, moderate-reddish-brown siltstone and very fine-grained, thin-bedded, pale-reddish-brown to grayish-red sandstone and mudstone. Planar, low-angle, and ripple cross-stratification are common. Isolated outcrops are difficult to distinguish from the Kayenta Formation. The upper contact is conformable and is placed between the highest, reddish-brown sandstone of the Dinosaur Canyon Member and the base of a 6 inch (0.1 m) thick, light-gray dolomitic limestone with algal structures that weathers to mottled colors of yellowish-gray, white, and grayish-orange-pink with dark-reddish-brown chert nodules. The Dinosaur Canyon Member is 200 feet (67 m) thick.

Whitmore Point Member (Jmw): This member is also well exposed in several areas of Warner Valley. It is composed of pale-red-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone. Several 2- to 6-inch- (5-15-cm-) thick beds of light-greenish-gray, dolomitic limestone contain algal structures and fossil fish scales of *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950). Unlike the St. George quadrangle to the west, there are about 5 feet (2 m) of red beds that look like the Dinosaur Canyon Member above the basal light-gray dolomitic limestone with algal structures (Higgins and Willis, 1995). These beds are assigned to the Whitmore Point Member. The conformable upper contact is mapped at the base of the massive, cross-bedded Springdale Sandstone Member. This member is 80 feet (26 m) thick.

Springdale Sandstone Member (Jms): The Springdale Sandstone Member of the Moenave Formation is best exposed along the west side of the quadrangle in Warner Valley. It is pale-reddish-brown to grayish-yellow, medium- to very thick-bedded, bedded, fine- to medium-grained, cross-bedded, ledge-forming sandstone with interbedded light-purple-gray siltstone near the middle. The sandstone weathers to pale pink, pinkish gray, yellowish gray, and pale reddish purple rounded cliffs and ledges that commonly have Liesegang banding. Some of the sandstone layers are characterized by small, resistant, 0.13-inch (2 mm) diameter concretions that give weathered surfaces a pimply appearance. In some areas the member also includes minor, thin, discontinuous lenses of intraformational conglomerate, with mudstone rip-up clasts. Poorly preserved petrified wood is locally abundant. The upper contact is drawn at the top of the massive sandstone and at the base of slope-forming, mudstone and claystone of the Kayenta

Formation.

In NW1/4NW1/4SW1/4 section 33, T. 43 S., R. 13 W., the beds just above the Springdale/Kayenta contact are composed of pale-red-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone that appear identical to the Whitmore Point Member. These beds even include fossil fish scales, probably of *Semionotus kanabensis*. I mapped this 10-foot (3-m) thick interval as part of the Kayenta Formation, thus including Whitmore Point-like beds in the lower Kayenta. These beds probably indicate a brief return to Whitmore Point-like depositional conditions at the close of Springdale time. This member is 120 feet (36 m) thick.

Kayenta Formation (Jk)

The Kayenta Formation displays a general coarsening upward sequence. Because of its transitional nature, the upper contact with the Navajo Sandstone is not consistent in the literature. In southwest Utah, generally west of the Hurricane fault, this transition zone can be several hundred feet thick (Tuesink, 1989; Sansom, 1992). Hintze and Hammond (1994) divided this formation into three members northwest of the Washington Dome quadrangle by putting the upper contact above the uppermost fluvial sequence, thus including a significant amount of eolian sand in the upper Kayenta. In this and adjacent quadrangles, we chose to use the contact from published work to the east that places it above the major break in topography created by the fluvial siltstone beds below the first major eolian sandstone, above which the sequence remains predominantly eolian (Moore and Sable, 1994; Doelling and Davis, 1989). As a result, much of what Hintze and Hammond (1994) placed in their upper member is herein included in the Navajo Sandstone. Dividing the remaining Kayenta beds into two members with a lower member extending to the top of a few thin dolomite beds that are roughly 100 feet (30 m) above the base seems to work reasonably well to the west (Higgins and Willis, 1995); however, this far east, the dolomite beds seem to be more randomly placed and do not provide a suitable horizon for dividing the formation. The Kayenta Formation is upper Pliensbachian to lower Toarcian in age (Early Jurassic) (Imlay, 1980). Total thickness of the formation is 900 feet (273 m).

The Kayenta Formation forms the base of Sand Mountain just north of Warner Valley in the southwest portion of the quadrangle, and is also exposed against the Hurricane fault zone on the down-dropped block. The lower slope-forming unit consists of interbedded, pale-reddish-brown to moderate-reddish-brown, thin-bedded siltstone; very fine-grained, moderately well-sorted, thin-bedded, planar to lenticular sandstone with climbing ripple marks; and moderate-purplish-red mudstone that has sericite on some bedding surfaces. The thin sandstone layers generally pinch out laterally and are typically calcareous. Their upper surface is locally bioturbated and mottled, varying in color from light greenish gray to moderate reddish brown. The dinosaur footprints in the northwest corner of section 30, T. 43 S., R. 13 W. are in these lower beds, just a few feet above the top of the Springdale Sandstone Member of the Moenave Formation. Previous publications (Miller and others, 1989) and the Bureau of Land Management sign at the track site incorrectly state that these footprints are in the Moenave Formation, when in fact they are well above the Springdale Sandstone Member of the Moenave Formation in the lower beds of the Kayenta Formation. Local beds of thinly laminated light-pinkish-gray to light-olive-gray, micritic dolomite weather in blocky chips. Intervals toward the middle of the formation commonly weather to punky, gypsiferous soil, although gypsum beds are seldom exposed.

The upper, coarser part of the formation comprises the majority of the rock that forms the cliff face along the south side of Sand Mountain. It consists of moderate-reddish-brown siltstone and pale-reddish-brown to light-purplish-red mudstone with interbedded pale-reddish-brown to pale-red sandstone. The planar bedding of these mudstone and siltstone layers, along with small-scale cross-bedding of the sandstone, indicates alluvial deposition. The mudstone and siltstone are generally slope forming, but the very fine-grained, usually calcareous sandstone forms thin ledges in the lower portion that thicken to small cliffs near the top. The upper contact with the Navajo Sandstone is transitional and difficult to correlate across the quadrangle, especially with complications created by faulting at the southeast corner of Sand Mountain. It is drawn at the top of the topographic break created by planar, water-lain, siltstone and sandstone. Above this break the sandstone is slightly lighter in color and very thick bedded with large-scale eolian cross-beds, above which the transitional sequence remains predominantly eolian.

Navajo Sandstone (Jn)

The Navajo Sandstone is the youngest Mesozoic formation exposed in the quadrangle. Although it is about 2,000 feet (610 m) thick in southwest Utah, only the basal 1,000 feet (305 m) are exposed within The Divide quadrangle. It forms the upper portion of the cliff face as well as the top of Sand Mountain. The basal transition zone is characterized by resistant, very thick-bedded, cross-bedded sandstone whose layers are separated by planar bedded, silty, fine-grained sandstone with thin mudstone interbeds. In addition to wavy bedding and dark flaser-like laminae, there are soft-sediment deformation features such as diapiric and load structures, and bioturbation (Sansom,1992). Except for the basal transition zone, this cross-bedded, eolian sandstone is pale- to moderate-reddish-brown and consists of fine- to medium-grained, well-rounded, well-sorted, frosted quartz grains. It weathers to sand that accumulates on outcrops and adjacent low areas. Locally, the sand is blown into dune form.

Quaternary

Basaltic Flows

Five Quaternary basaltic flows are present within The Divide quadrangle as part of the western Grand Canyon basaltic field (Hamblin and Best, 1970), a large area of late Tertiary to Holocene basaltic volcanism in northwestern Arizona and southwestern Utah (Hamblin, 1970a; Best and Brimhall, 1974). Because they are resistant to erosion and were erupted in a “geological instant,” these flows help to evaluate rates of local tectonic and geomorphic development. Downcutting of the streams along the sides of the resistant basalt flows create "inverted" valleys (Hamblin, 1970a, 1987; Hamblin and others, 1981). Typically, the oldest inverted valleys are now at the highest elevations above present drainages. Since downcutting has been the dominant geomorphic process during the late Cenozoic, the relative height above drainages provides a way of estimating relative age of the flows, and, coupled with radiometric dating, allows determination of a downcutting rate for the area. Hamblin and others (1981) calculated a downcutting rate of 300 feet (90 m) per million years for the structural block that includes the west half of The Divide quadrangle, west of the Hurricane fault zone. Hamblin (1970a, 1987) mapped flows in the region as stages I to IV, based on the amount of topographic inversion and erosion of the flows. Stage I are high remnants that bear no apparent relation to the present topography, whereas stage IV are very young flows with little or no topographic inversion. However, this system is only valid for comparisions within a large structural block. Flows that cross and are offset by the Hurricane fault zone, such as the Remnants flow, illustrate that the amount of erosional down-cutting is largely a function of the amount and rate of relative uplift. Thus, near areas with a complex down-cutting history, the stage designations become misleading.

Sanchez (1995) and Smith and others (1999) studied the composition and evolutionary history of the flows in the Hurricane volcanic field, which includes four of the five flows within The Divide quadrangle, as well as theoretical aspects of mantle properties beneath the Basin and Range and Colorado Plateau transition zone. They classified these volcanic rocks as low-silica basinites, basinites, and alkali basalts on the total alkali verses silica (TAS) diagram of Le Bas and others (1986). Sanchez (1995) and Smith and others (1999) also discussed the trace element geochemistry for these rocks and suggested that they represent magmas that had an oceanic island basalt (OIB)-like garnet-free source, but that show variable amounts of mixing with lithospheric mantle. The primitive geochemistry of the low-silica basinite and basinite suggests that they rose rapidly from a site of partial melting to the surface. Sanchez (1995) showed that the geochemical variation among the basalts of the greater Hurricane area cannot be due to simple fractional crystallization of a single magma, similar to the findings of Best and Brimhall (1974), who studied basaltic rocks of the western Grand Canyon region.

The location of vents in the Hurricane volcanic field seems to be controlled by joints instead of faults (Sanchez, 1995). Sanchez indicated that cone alignments match local joint maxima data of Lefebvre (1961). He also showed that most cones in the area are monocyclic (single event) and monogenetic (single source), meaning that most erupted from a single source over a relatively short time span (probably less than 100 years).

Several flows in The Divide quadrangle consist of more than one cooling unit (cooling units are lava pulses from the same eruption separated by short time intervals, whereas flows are from different eruptions and are separated by enough time for weathering to occur). Some of the ridges, like the Remnants flow, may be composed of multiple flows. All of the flows are partly covered by a veneer of eolian sand and pedogenic carbonate, which is mapped as a stacked-unit deposit. Cinder cones are mapped using the flow symbol followed by a ‘c’.

Gould Wash flow (Qbgw): The Gould Wash flow, whose source is a cinder cone 2 miles (3.2 km) to the east of The Divide quadrangle, cuts across the northeast corner of the quadrangle. This dark-gray, very fine-grained olivine basalt has abundant olivine phenocrysts up to 1 mm in size, which is the only recognizable mineral in hand sample. Geochemically, the flow is classified as a basalt on the TAS diagram of Le Bas and others (1986) (figure 6, appendix). Downing (2000) reported an $^{40}Ar/^{39}Ar$ age of 0.278 $\pm$ 0.018 for this flow. The Gould Wash flow is generally 20 to 30 feet (6-9 m) thick and is only a few feet above current base level.

[Figure 6 near here]

<u>The Divide flow and cinder cones (Qbd, Qbdc)</u>: The Divide flow (Qbd) is dark-gray and very fined-grained with phenocrysts of olivine. It is classified as basanite on the TAS diagram of Le Bas and others (1986), according to geochemical data from 19 samples collected by Sanchez (1995) and seven additional samples for this report (figure 6, appendix). The flow still has a relatively fresh surface morphology even though a sample taken from near the top of the cascade over Hurricane Cliffs in SW1/4SE1/4 of section 3, T. 43 S., R. 13 W. yielded an $^{40}Ar/^{39}Ar$ age of 0.41 ± 0.08 Ma. The lava cascade itself is actually two remnants of the flow; the large one on the front of the cliff and the other one in the small drainage just to the south (figure 7). Both are isolated from the rest of the flow by the massive cliff of the Fossil Mountain Member of the Kaibab Formation. Similarly, the cascade abruptly ends at the top of the massive cliff of the Brady Canyon Member of the Toroweap Formation, 300 feet (92 m) above the current level of the alluvial fan. Both the thickness and the eroded nature of the end of the cascade indicate that it probably once extended downhill beyond its current extent 400 feet (122 m) below the top of the cliffs. Obviously, any lava that might have reached the down-dropped block of the Hurricane fault is now covered by alluvium and talus. It is safe to conjecture that about 400,000 years ago, the fault scarp of the Hurricane Cliffs was at least 400 feet (122 m) tall.

[Figure 7 near here]

Two cinder cones (Qbdc) are associated with The Divide flow. There are bombs up to 6 feet (2 m) in diameter and agglutinate near the summit of the southernmost of the two cones. The way the bombs are stretched suggests that lava flowed downslope after impact (Sanchez, 1995). The cones are being extensively eroded along the east flank by intermittent flow in a north-draining wash.

Two dikes, mapped as one outcrop, strike north-south in the SW1/4SW1/4 of section12, T. 43 S., R. 13 W. and extending into the NW1/4NW1/4 of section 13, T. 43 S., R. 13 W. The northern dike starts about 0.6 miles (1 km) south and a little east of the southern cinder cone. It extends about 1,300 feet (397 m) and is 5 feet (1.5 m) wide. This dike includes abundant xenoliths of Moenkopi Formation red beds, presumably from the middle red member that surrounds it, which can reach 1 inch by 2 inches (3 x 5 cm) in size. Continuing south but beginning about 30 feet (9 m) to the east from the end of the first dike, a second dike extends another 650 feet (198 m) but is only two feet (0.6 m) wide. Sanchez (1995) interpreted the dikes to be conduits for the two cones. The dikes may have been a partial source of the flow, especially since the eastern extent of the southern isolated outcrops of the flow appear higher in elevation than the cinder cones.

<u>Ivan's Knoll flow (Qbi)</u>: Ivan's Knoll flow extends from the north into the northwest corner of The Divide quadrangle. Just north of the quadrangle are small cinder deposits of a highly eroded source area for this flow (Sanchez, 1995; Biek, 1998). The edge of the flow is eroded, exposing generally at least two flow units underlain by Navajo Sandstone. It forms a well exposed, resistant ridge north of Sand Hollow Draw that stands about 200 feet (61 m) above local drainages.

Of the five samples reported in Biek (1998) and eight samples reported in Sanchez (1995) from this flow, only one was collected from within The Divide quadrangle. Geochemical analysis of these samples classify Ivan's Knoll flow as a basalt on the TAS diagram of Le Bas and others (1986) (figure 6, appendix). In hand sample, the flow is a medium-gray, fine- to medium-grained olivine basalt, with olivine phenocrysts up to about 0.1 inch (3 mm) across. Olivine is the only recognizable mineral in hand sample. The Ivans Knoll flow yielded $^{40}Ar/^{39}Ar$ ages of 0.97 $\pm$ 0.07 Ma and 1.03 $\pm$ 0.02 Ma (Bob Biek, Utah Geological Survey, verbal communication, January 31, 2000). The flow also yielded a normal paleomagnetic signature (Mike Hozik, Stockton College, verbal communication, 1999), fortuitously recording the short-lived Jamarillo magnetic reversal event. Within The Divide quadrangle, the Ivan's Knoll flow is 15 to 25 feet (5-8 m) thick.

Remnants flow (Qbr): The Remnants flow is the only flow within the quadrangle that is present on both the hanging wall and the footwall of the Hurricane fault. The portion of the flow that sits on the footwall has been eroded into five segments: the northern three overlie the lower red member of the Moenkopi Formation and are known as the "Three Brothers;" to the south lies "White Face," so named for the underlying ledge of Virgin Limestone; the southernmost basalt-capped butte is called "The Wart" and also overlies the lower red member. The flow that caps Mollies Nipple, to the north in the Hurricane quadrangle, is geochemically different from this flow and is likely related to the Ivan's Knoll flow rather than the Remnants flow, as was previously supposed from geomorphological comparisons (Biek, personal communication, 1999). These remnants are approximately 350 feet (106 m) higher than the surrounding topography. The portion of the flow west of the Hurricane fault, however, is partly buried by Quaternary sediment (figure 8), as evidenced by the gravel pit operation along the north edge of the flow.

[Figure 8 near here]

The geochemistry of Sanchez's (1995) two samples from "White Face" and one from "The Wart" classifies this flow as a low-silica basanite on the TAS diagram of Le Bas and others (1986), as do the six samples collected for this report (four from west of the fault and two from the "Three Brothers") (figure 6, appendix). The Remnants flow yielded $^{40}Ar/^{39}Ar$ ages of 1.06 $\pm$ 0.03 Ma and 0.94 $\pm$ 0.04 Ma. From the paleotopographic profile of the basalt caps and the large amount of scoria present, as well as the sandstone inclusions in the basalt that caps the southern two of the "Three Brothers," it is probable that the source of this flow is just west of and perhaps includes the southern two of the "Three Brothers." At least three flow units are present on the middle of the "Three Brothers," but in most places, only one is obvious. This dark-brownish-black to dark-gray, medium-grained olivine basalt reaches approximately 40 feet (12 m) thick.

Grass Valley flow and cinder cone (Qbg, Qbgc): The Grass Valley flow is a very dark gray, fine- to medium-grained olivine basalt. Geochemical data from twelve samples collected by Sanchez (1995) and six for this report indicate that this flow plots as an alkali (trachy-) basalt on the TAS diagram of Le Bas and others (1986) (figure 6, appendix). The flow has been offset, down to the northwest, by two faults that trend northeast. The southernmost of the two faults has offset the flow approximately 20 feet (6 m) while the northernmost has a minimum offset of 150 feet (46 m) with sediment covering the down-dropped block next to the fault. Additionally, from some perspectives, the entire flow appears tilted toward the east into the Hurricane fault; however, part of this tilt may be due to the paleotopography on the Navajo Sandstone over which the basalt flowed. The Grass Valley flow yielded an $^{40}Ar/^{39}Ar$ age of 1.47 $\pm$ 0.34 Ma (Bill Lund, Utah Geological Survey, written communication, July 14, 2000). The partially eroded Grass Valley cinder cone (Qbgc) has a 10 foot (3 m) thick basalt probably cooled from a lava lake and two dikes, about 10 feet (3 m) wide that radiate from the center (Sanchez, 1995).

Alluvial Deposits

Alluvial-fan deposits (Qafy, Qafo): Alluvial-fan deposits include poorly to moderately sorted, boulder-to clay-size sediment at the base of the Hurricane Cliffs and locally at the mouth of active drainages. Younger alluvial-fan deposits (Qafy) form on active depositional surfaces while older alluvial-fan deposits (Qafo) are deeply dissected. Alluvial-fan deposits vary from 0 to about 50 feet (0-15 m) thick.

Stream-terrace deposits (Qat_3): Well-rounded, pebble- to cobble-size clasts in a muddy- to coarse-sand matrix form a poorly sorted, indurated pedogenic carbonate-cemented conglomerate 30 to 90 feet (9-27 m) above the modern floodplains of Fort Pearce Wash. Using an approximate downcutting rate of 300 feet (90 m) per million years (Hamblin and others, 1981) for this structural block, level 3 deposits are estimated as 100,000 to 300,000 years old. The thickness of these stream-terrace deposits varies from 0 to about 40 feet (0-12 m)

Stream deposits (Qal_1, Qal_2): Moderately to well-sorted, clay to fine gravel deposits are mapped in the larger, active drainages, including Fort Pearce Wash and its tributaries. Qal_1 includes deposits in, and up to 10 feet (3 m) above, current channels and is 0 to 10 feet (0-3 m) thick. Qal_2 deposits are adjacent to and dissected by drainages containing Qal_1 deposits and are 10 to 30 feet (3-9 m) above active channels. They are 0 to 20 feet (0-6 m) thick.

Colluvial Deposits (Qc)

Colluvial deposits are poorly sorted, angular to rounded blocks in a muddy to sandy matrix that are deposited by sheet wash and slope-creep on moderate slopes. Only the larger deposits have been mapped. Locally, this unit includes eolian, talus, and debris-flow and alluvial deposits too small to map separately. Thickness of these deposits varies from 0 to 20 feet (0-6 m).

Eolian Deposits

Caliche and eolian sand deposits (Qeo): These deposits form planar surfaces covered with abundant Stage IV pedogenic carbonate (caliche) (Birkeland and others, 1991) and lesser amounts of eolian sand. They are mapped on the Navajo Sandstone of Sand Mountain where the planar surfaces are of higher relief than the surrounding sandstone. They generally range from 0 to 10 feet (0-3 m) thick.

Eolian dune sand deposits (Qed): These deposits consist of well- to very well-sorted, very-fine- to medium-grained, well-rounded, usually frosted, mostly quartz sand blown into dune form on

Sand Mountain and in Warner Valley. The sand is derived primarily from weathering of the Navajo Sandstone. Some of the transverse dunes in the main dune field on Sand Mountain, just west of the quadrangle, are 40 feet (12 m) high. Thickness varies from 0 to 40 feet (0-12 m).

Eolian sand deposits (Qes): These deposits consist of well- to very well-sorted, very fine- to medium-grained, well-rounded, usually frosted, mostly quartz sand that has accumulated in irregular hummocky mounds on the lee side of ridges as well as on Sand Mountain and in Warner Valley. In many areas, the blowing sand is partially stabilized by sparse vegetation. Most of the sand was probably derived from weathering of the Navajo Sandstone and the Kayenta Formation. Locally, it forms poorly developed dunes. Thickness varies from 0 to 50 feet (0-15 m).

Mass-Movement Deposits

Landslide deposits (Qms): Several landslide deposits are mapped near the east side of the quadrangle along the southwest edge of Little Creek Mountain. The deposits consist of very poorly sorted debris ranging in size from clay to blocks several feet across, and form chaotic, hummocky mounds. Basal detachments develop on the middle red member of the Moenkopi Formation. The mass-movements involve overlying bedrock formations and talus. The thickness of these deposits is highly variable.

Talus deposits (Qmt): Talus deposits are very poorly sorted, angular boulders with minor fine-grained interstitial sediments that have accumulated on and at the base of steep slopes. Most talus deposits consist of jointed blocks of basalt that roll down slopes created as the supporting softer sedimentary beds erode. Similarly, blocks of the Shinarump Conglomerate Member of the Chinle Formation accumulate on the upper red member of the Moenkopi Formation and blocks of Kayenta Formation and Navajo Sandstone rest on the lower slopes of Sand Mountain. Along the Hurricane Cliffs, blocks of the Fossil Mountain Member of the Kaibab Formation and the Brady Canyon Member of the Toroweap Formation also collect on the steep slopes. Only large deposits were mapped, but talus boulders are common on all steep slopes in the quadrangle. Thickness varies from 0 to 20 feet (0-6 m).

Mixed-Environment Deposits

Mixed alluvial and colluvial deposits (Qac, Qaco): Poorly to moderately sorted clay- to boulder-sized sediment is mapped in minor drainages throughout the quadrangle. The alluvial deposits are transported along washes during heavy rainstorms whereas colluvial material is derived from side slopes along the washes. Qaco deposits are higher than and being dissected by current drainages. In some areas, much of what is deposited as Qac is being derived from Qaco. These deposits are gradational with colluvial deposits and include level 1 and 2 alluvial deposits (Qal_1, Qal_2) too small to map separately. They vary in thickness from 0 to 10 feet (0-3 m).

Mixed alluvial and eolian deposits (Qae): These deposits consist of moderately to well-sorted clay- to sand-sized sediment of alluvial origin that locally include abundant eolian sand and minor gravel. They are deposited in large, open, nearly flat areas, are generally finer grained than other surficial deposits, and have minor pedogenic carbonate (caliche) development. They are mapped in small valleys east of the Hurricane Cliffs and in Grass Valley. The deposits are typically 0 to 30 feet (0-9 m) thick, but locally may be thicker.

Mixed eolian and alluvial deposits (Qea): These deposits are composed mostly of well-sorted eolian sand but locally include alluvial clay- to gravel-size material. They have been locally reworked by alluvial processes and are starting to develop a pedogenic carbonate horizon. These deposits flank Sand Mountain in areas of Warner Valley that include small drainages which rework much of the sand and add an alluvial component. A Quaternary fault scarp on the Warner Valley fault 1,800 feet (545 m) long offsets these deposits 9 feet (3 m). The scarp trends north-northeast from the NE1/4NW1/4 of section 28, to SE1/4SW1/4 of section 21, T. 43 S., R. 13 W. These deposits are typically 0 to 20 feet (0-6 m) thick.

Stacked-Unit Deposits

Eolian sand and pedogenic carbonate over basalt flows (Qec/Qbgw, Qec/Qbd, Qec/Qbi, Qec/Qbr, Qec/Qbg): Each basaltic flow in The Divide quadrangle is partly concealed by eolian sand and pedogenic carbonate (up to stage V of Birkeland and others, 1991). These deposits are discontinuous and generally less than 3 feet (1 m) thick

Artificial-fill deposits (Qf)

Artificial fill used for dams and levees is mapped throughout the quadrangle. It consists of engineered fill and general borrow material. Although only a few deposits are mapped, fill should be anticipated in all developed areas, many of which are shown on the topographic base map. Thickness is highly variable.

STRUCTURE

Regional Setting

The Divide quadrangle is in the transition zone between the Colorado Plateau and the Basin and Range physiographic provinces and contains structural elements of both (Hamblin, 1970b; Hintze, 1986a). The Colorado Plateau, relatively coherent and tectonically stable, is underlain by generally horizontal sedimentary strata that are locally disrupted by early Tertiary Laramide basement-block uplifts, Oligocene/Miocene igneous intrusions, and Late Tertiary to Quaternary basalt flows. The Basin and Range Province is characterized by roughly east-west extensional tectonics which creates north-south trending horsts and grabens and widespread igneous activity. Both provinces have experienced broad epeirogenic uplift.

The transition zone roughly coincides with the leading edge of the Late Cretaceous to early Tertiary Sevier orogenic thrust belt. Rocks in the area are involved in folds and minor detachments in front of the main thrust belt, and a basal detachment is postulated in underlying Cambrian strata (Davis, 1999). At the frontal portion of most thrust belts, a detachment at depth transfers the waning displacement of the thrust belt through a triangle zone characterized by a reverse fault that helps create an anticline commonly tens of miles in length. The development of the fold effectively uses up the remaining displacement of the thrust belt. In this area, the basal detachment is believed to lie within the Cambrian Bright Angel Shale and the frontal fold is the Virgin anticline, whose axis is just west of the quadrangle boundary.

The transition zone is also part of the active southern segment of the Intermountain Seismic Belt, which coincides with the boundary between relatively thin lithosphere of the Basin and Range Province and thicker more stable lithosphere of the Colorado Plateau (Arabasz and Julander, 1986). The zone consists of a series of down-to-the-west normal faults that step down from the Colorado Plateau into the Basin and Range Province. The greater St. George area lies on the intermediate block between the two major fault zones. The block is bounded on its eastern edge by the Hurricane fault (Hamblin, 1970b) and on its western edge by the Grand Wash and Gunlock faults (figure 1). Displacement on the Hurricane fault zone increases to the north (Hamblin, 1970b) whereas displacement on the Grand Wash/Gunlock increases to the south (Hintze, 1986b). Schramm (1994) postulated that these faults form a displacement transfer zone, where decreasing slip on one fault is compensated for by increasing slip on another. This type of transfer zone could account for the relatively wide width of the transition zone in southwestern Utah. The Divide quadrangle straddles the eastern edge of this intermediate block.

The regional dip of the rocks in the intermediate-level block, which includes the west half of The Divide quadrangle, is to the northeast at 5 to 10 degrees. Strata in the block are compressed into three northeast-trending folds: the broad St. George syncline, the axis of which goes through St. George City; the much tighter Virgin anticline, the axis of which is approximately 5 miles (8 km) west of The Divide quadrangle; and the broad Sand Mountain syncline, whose east limb is included within The Divide quadrangle. East of this syncline, folding and faulting in east Warner Valley and along the Hurricane fault create more complex features. Rocks east of the Hurricane fault, which are part of the Colorado Plateau province, dip eastward about 10 degrees near the fault, but their dip decreases to about 2 degrees along the east edge of the quadrangle.

Folds

Sand Mountain syncline

Strata of Sand Mountain and western Warner Valley, just off the west side of the quadrangle, are folded into a very broad, poorly defined syncline. The fold is best expressed by the change in strike of the cliffs of the Kayenta Formation around the south and west edges of Sand Mountain. The axis trends northeast but is not well defined because the fold is so broad and because of the massive nature of the Navajo Sandstone. Only the east limb of the Sand Mountain syncline is included in The Divide quadrangle.

Warner Valley dome

The Warner Valley dome is located near the south edge of the quadrangle in east Warner Valley about 1.5 miles (2.4 km) west of the Hurricane fault zone (figure 9). The dome is cut by and bounded on both sides by normal faults creating a pod-shaped horst of Triassic rocks; however, not all of the folding is easily attributed to faulting and the formation of the horst. It is probable that the dome is a result of Sevier orogenic compression, similar to the Virgin Anticline, and then subsequently cut and modified by extensional normal faults.

[Figure 9 near here]

The dome was drilled as a petroleum prospect in 1960 by Intex Oil. The Skyline #1 well, spudded in the middle red member of the Moenkopi Formation, was drilled to a total depth of 3,006 feet (917 m). No mention of oil or gas shows is made in drilling records, only that drilling encountered the Toroweap Formation at 905 feet (276 m), the Coconino (Queantoweap) Sandstone at 1,425 feet (435 m) and the Pakoon Dolomite at 2,745 feet (837 m).

Normal Faults

Hurricane fault zone

The Hurricane fault zone is a major, active, high-angle, west-dipping normal fault system that stretches at least 155 miles (250 km) from south of the Grand Canyon to north of Cedar City. The total stratigraphic separation generally increases northward along the fault from less than 200 feet (61 m) south of the Grand Canyon (Hamblin, 1970b) to 8,265 feet (2,520 m) near Toquerville (Stewart and Taylor, 1996). The Hurricane fault zone has been called a normal dip-slip fault (Huntington and Goldthwait, 1904; Gardner, 1941; Cook, 1960; Averitt, 1962; Hamblin, 1965,1970b; Kurie, 1966; and Stewart and Taylor, 1996), a reverse fault (Lovejoy, 1961), and even a fault zone with a significant component of left-lateral slip (Moody and Hill, 1956; and Anderson and Barnhard, 1993). However, recent studies in the greater Hurricane area (Schramm, 1994; Stewart and Taylor, 1996; Biek, 1998; Lund and Everitt, 1998) show that Pliocene to Quaternary displacement on the Hurricane fault zone is normal dip-slip, locally with a slight right-lateral component of displacement. No evidence was found to support the Hurricane fault zone being a reactivated Sevier-age structure.

Because of the great length of the Hurricane fault, it almost certainly ruptures in segments, although true seismogenic segments are not yet clearly defined (Stewart and others, 1997; Lund and Everitt, 1998). The greatest number and best preserved scarps, at the north end of the fault zone, indicate that the most recent faulting on the Hurricane fault zone in Utah occurred in the latest Pleistocene or early Holocene (Lund and Everitt, 1998). Lund and Everett (1998) postulated that multiple surface-faulting earthquakes have occurred in the late Quaternary along most, if not all, of the Utah portion of the fault zone.

The most detailed study to date of the slip rate of the Hurricane fault zone in Utah (Lund and Everitt, 1998) indicated that displaced alluvial surfaces at Shurtz Creek near Cedar City, which are tentatively dated on the basis of soil profile development, provide a minium slip rate of 0.11 mm/yr for approximately the past 100,000 years. In addition, $^{40}Ar/^{39}Ar$ age estimates for displaced basalt flows erupted from the Pintura volcanic center, north of The Divide quadrangle, provide a slip rate of 0.39 mm/yr over the past 900,000 years. This rate correlates well with a preliminary slip-rate estimate of 0.46 mm/yr using the Remnants flow that crosses and is offset by the fault zone within The Divide quadrangle. $^{40}Ar/^{39}Ar$ data from a sample west of the fault zone indicates the basalt is 1.06 ± 0.03 Ma while a sample collected from east of the fault zone, from the middle of the Three Brothers, indicates an age of 0.94 ± 0.04 Ma. Using 4,575 feet (1,395 m) as a gross estimate of stratigraphic separation and an average flow age of 1.0 Ma results in a slip rate calculation maximum of 0.46 mm/yr over the past million years. Additional work on geochemical correlation and refinement of the amount of separation to account for any eastward tilting of the hanging-wall block is underway. This slip rate could be reduced if the source of the flow was on the east side of the fault, which would indicate the possibility of cascading and thus reduce the amount of net vertical displacement. The Divide flow did cascade over the Hurricane Cliffs. A sample taken from near the top of the cascade in SW1/4SE1/4 of section 3, T. 43 S., R. 13 W. yielded an $^{40}Ar/^{39}Ar$ age of 0.41 $\pm$ 0.08 Ma. The cascade abruptly ends at the top of the massive cliff of the Brady Canyon Member of the Toroweap Formation, 300 feet (92 m) above the current level of the alluvial fan. Both the thickness and the eroded nature of the end of the cascade indicate that it probably once extended beyond its current limit of 400 feet (122 m) downslope from the top of the cliffs. It is safe to conjecture that about 400,000 years ago, the fault scarp of the Hurricane Cliffs was at least 400 feet (122 m) tall, thus providing a minimum slip rate of approximately 0.30 mm/yr for the last 400,000 years.

Heading north from the Utah/Arizona border at the south edge of The Divide quadrangle, the Hurricane fault zone strikes N30^{o}E for 1.5 miles (2.4 km) to the mouth of a large, unnamed drainage. Along this segment, the fault zone reaches about 1,600 feet (488 m) wide and includes up to six mapable faults in bedrock units. A fault scarp 10 feet (3 m) high is located in the NE1/4 of section 34, T. 43 S., R. 13 W., where the Brady Canyon Member of the Toroweap Formation is next to a nearly vertical section of the Virgin Limestone Member and red beds of the Moenkopi Formation that have been caught in the fault zone between the Permian rocks and the Jurassic Kayenta Formation. Additionally, Lund and Everett (1998) identified possible isolated, colluvium-mantled, bedrock-cored scarps that are as much as 20 feet (6 m) high in the SW1/4 and the NE1/4 of section 34 which would indicate recurrent surface-faulting earthquakes occurred during the late Quaternary; however, young stream-terrace deposits (likely middle to late Holocene) at the mouth of the large, unnamed drainage are not displaced, which would indicate an absence of geologically recent faulting on this portion of the fault. Just north of this drainage, cross section A-A’ shows 4,800 feet (1464 m) of displacement across the Hurricane fault zone (figure 10).

[Figure 10 near here]

From the large, unnamed drainage described above, the Hurricane fault zone trends N20^{o}W for 5.25 miles (8.45 km), turns to N20^{o}E for 0.5 miles (0.8 km), and continues nearly north for the remaining almost 2 miles (3 km) of the quadrangle. The base of the Hurricane Cliffs is covered by alluvial-fan and other Quaternary deposits so that bedrock outcrops in the hanging wall, either the Jurassic Kayenta Formation or Navajo Sandstone, are anywhere from 0.2 to 2 miles (0.3-3 km) west of the base of the cliffs, except for outcrops of Moenkopi Formation red beds smeared in the fault zone near the base of the cliffs. There is only one area, about 0.75 miles (1.2 km) north of the large, unnamed drainage, where a nearly complete section can be seen across the fault zone. There, the fault zone is almost 0.5 miles (0.8 km) wide with most of the displacement taken up by a fault in the middle of the zone. Heading west from the Woods Ranch Member of the Toroweap Formation exposed in the Hurricane Cliffs, these normal faults drop rock down-to-the-west beginning with the Fossil Mountain Member of the Kaibab Formation, then the Rock Canyon Conglomerate and Timpoweap Members of the Moenkopi Formation, followed by Moenkopi red beds and Petrified Forest Member of the Chinle Formation that are partially covered by Quaternary alluvial deposits, and finally the Kayenta Formation. Continuing to the west, there is also an antithetic fault within the Kayenta Formation. Due to cover by alluvial-fan deposits, the only other instructive exposure of the Hurricane fault in The Divide quadrangle is nearly 4 miles (6.4 km) to the north, in the NW1/4 of section 3, T. 43 S., R. 13 W., where the Brady Canyon Member of the Toroweap Formation is in fault contact with older alluvial deposits and Moenkopi red beds. Apparently, the younger quaternary units are not faulted (Lund and Everitt, 1998), indicating that no late Quaternary surface rupture has occurred on this portion of the fault.

Warner Valley fault

The Warner Valley fault bounds the west side of the Warner Valley dome and is a normal fault with down-to-the-west movement. This fault places the Kayenta Formation next to the Shnabkaib Member of the Moenkopi Formation, creating 1,800 feet (549 m) of displacement, where cross section A-A' crosses the map. Displacement decreases southward, as the fault dies out in northern Arizona, but increases northward until it is buried by alluvial fan deposits. It probably connects to or is perhaps en echelon with the Hurricane fault zone. A Quaternary fault scarp on the Warner Valley fault 1,800 feet (545 m) long offsets a unit of mixed eolian and alluvial sediments (Qea) 9 feet (3 m). The scarp trends north-northeast from the NE1/4NW1/4 of section 28, to SE1/4SW1/4 of section 21, T. 43 S., R. 13 W. At this latitude, the most recent faulting has occurred 1.5 to 2 miles (2.4-3.2 km) west of an eastward bend in the Hurricane fault zone near the Utah/Arizona border.

Other normal faults

The east side of the Warner Valley dome is cut and bounded by a normal fault with down-to-the-east movement, thus creating a pod-shaped horst. This unnamed fault has an offset of about 1,000 feet (305 m) where cross section A-A' crosses the map. The fault is probably an antithetic fault created in response to the eastward curvature of the Hurricane fault zone, although this fault duplicates that curve and closes the south end of the pod-shaped horst as it joins with the Warner Valley fault near its southern terminus.

Numerous other normal faults exist, mostly in the southwest quadrant of the quadrangle. The Navajo Sandstone and Kayenta Formation on the southeast corner of Sand Mountain are broken by several sets of northeast trending faults that form small grabens. These faults accommodate monoclinal flecture, variously called "down bending" (Gardner, 1941) and "reverse drag" (Hamblin, 1965), down toward the Hurricane fault zone. At least some of these faults probably extend south into Warner Valley and north through the Grass Valley flow, but they cannot be traced with certainty through Quaternary unconsolidated deposits. Other small faults with minor offsets are mapped within the pod-shaped horst of Triassic rocks and east of the horst toward the Hurricane Cliffs. Three small faults cut the Remnants flow and one is mapped that offsets the Ivan's Knoll flow.

Joints and Fractures

All competent bedrock units in the quadrangle are fractured, but the most prominent joints are in the massive sandstone beds of the upper portion of the Kayenta Formation and the Navajo Sandstone which forms Sand Mountain, and in the Shinarump Conglomerate Member of the Chinle Formation that caps Little Creek Mountain. The joints in the Shinarump

Conglomerate Member are generally spaced from a few feet to a few tens of feet and form a conjugate set subparallel to the strike and dip of bedding. The joints control the Liesegang banding of iron-manganese oxides, commonly forming “picture stone.”

Willis and Higgins (1995) recognized three main types of joints in the extensive exposures of Navajo Sandstone of the Washington quadrangle to the northwest. Two of them are recognized in The Divide quadrangle where the Navajo crops out from beneath the sand that covers much of Sand Mountain. The first type are generally parallel, high-angle, open joints. Spacing is generally uniform over large areas although there are areas of higher joint density. They form a very prominent joint pattern in the rock as they trend generally north but swing slightly northeast. In several areas these joints form a conjugate set with northwest-trending joints. Joints in this category are generally not healed or recemented and in many areas they are differentially weathered, forming straight, narrow gaps in the rock a few inches to several feet wide and locally more than 50 feet (15 m) deep.

The second type of fractures are less pervasive, but form very prominent features on aerial photographs. These joints are widely spaced, high-angle, parallel joints that mostly trend northeast. They are distinguished by strong siliceous and calcareous recementation that is generally more resistant than the country rock, causing them to weather out in relief to form prominent linear ridges. There is generally some brecciation near the fracture and in a few cases cross-beds in the sandstone are offset up to a few feet.

ECONOMIC GEOLOGY

A variety of geologic resources have been used from The Divide quadrangle. Gravel, sand, road fill, and riprap are currently in high demand because of rapid growth in the area. Stone is used for construction and ornamental purposes. There has also been minor gypsum exploration within the quadrangle, as well as exploration for petroleum, uranium, and paleoplacer deposits of precious metals; however, none of these potential resources are currently being developed. Also, the Springdale Sandstone Member of the Moenave Formation, host to the silver, copper, and uranium mineralization in the Silver Reef mining district, is present in the quadrangle (Proctor and Brimhall, 1986).

Gravel, Road fill, Riprap, and Sand

Gravel, essential for construction, is the most important geologic resource in The Divide quadrangle. The primary deposits are in alluvial fans associated with the Hurricane Cliffs and stream-terrace deposits along Fort Pearce Wash, with the largest active pit being on the north edge of the quadrangle in alluvial-fan deposits. Some older gravel deposits are cemented with thick pedogenic carbonate (caliche). Most active pits are in the deposits which are relatively younger and contain less carbonate.

Road fill was also acquired from deposits mapped as Qea and Qaco. A few other small excavations for limited uses are scattered through other parts of the quadrangle. Large talus boulders from Shinarump Conglomerate and basalt flows are used as riprap, especially along the base of artificial-fill deposits. Sand for local uses has been obtained from eolian sand deposits (Qes) near Fort Pearce Wash and in north Warner Valley.

Building Stone

Blocks of sandstone from the Kayenta Formation are harvested from the talus in the east end of Warner Valley at the base of “Noah’s Ark”, the informal local name for the big, red mountain in front of the Hurricane Cliffs. The blocks are used for landscaping and retaining walls (Larry Gore, Bureau of Land Management, verbal communication, May 27, 1999). No rock quarries for building stone have been developed in The Divide quadrangle; however, outcrops of flagstone in the Timpoweap and Kayenta Formations are extensive.

Ornamental Stone

Petrified wood from the Petrified Forest Member of the Chinle Formation is used to construct monuments, decorate rock gardens and fireplace mantles, and to sell as curiosities in gift shops. "Picture rock" or "landscape stone" from the sandstone beds within the Petrified Forest and Shinarump Conglomerate Members of the Chinle Formation is polished into spheres, coasters, and clock bases, and is cut into slabs that are mounted in picture frames. Currently, there are no quarries for this stone within the quadrangle, but several outcrops of picture rock exist. Picture rock is well-cemented sandstone with extensive Liesegang banding that imparts alternating light-brown, dark-brown, and orangish-brown swirls, bands, and other patterns in the rock. In cut pieces, these complexly intertwined bands resemble landscape silhouettes.

Gypsum

Exploration of the Harrisburg Member of the Kaibab Formation for economic deposits of gypsum has been hindered by its location along or near the top of the Hurricane Cliffs. The area of outcrop is limited by the Timpoweap Member of the Moenkopi Formation, which is resistant enough to cap the cliff in most places within the quadrangle. The gypsum of the Harrisburg Member is pale gray to white with bands of clay and limestone. Thicknesses of gypsum intervals within the Harrisburg Member vary due to secondary flowage, but outcrops are typically 10 to 30 feet (3-9 m) thick. The Shnabkaib Member of the Moenkopi Formation also has bedded gypsum, but beds are thin and contain abundant claystone and sandstone contaminants. No gypsum has been mined from the quadrangle.

Metals

In his reconnaissance examination of copper-uranium deposits west of the Colorado River for the U.S. Atomic Energy Commission, Everhart (1950) included the “Fort Pearce deposit in a Chinle sandstone” as a source of uranium. This location, near the southwest corner of the quadrangle just south of the north line of section 31, T. 43 S., R. 13 W., is also included in subsequent work by Finch (1967), which was also prepared partly on behalf of the Atomic Energy Commission. The mine shaft is currently still about 10 feet (3 m) deep and supported by lumber that is part of the mine works. Two other uranium prospects exist along the south border of the quadrangle in the SE1/4 of section 31, T. 43 S., R. 13 W. Uranium and vanadium was produced from the mineral carnotite in these sandstones from the Silver Reef mining district for several years beginning in 1950 (Proctor and Brimhall, 1986).

Finch and others (1987) included the east half of the quadrangle as having possible deep-seated, solution-collapse breccia pipes that could be potential hosts for economic deposits of copper and uranium minerals (Wenrich, 1985). Those pipes that originate in the deeply buried Mississippian Redwall Limestone provide the proper lithotectonic setting for such mineralization (Wenrich and Sutphin, 1989). Currently, the best way to determine mineralization is by drilling since deep-seated structures cannot be distinguished with certainty by their surface appearance from shallow collapse structures caused by the removal of gypsum (Wenrich and Huntoon, 1989). Additionally, some deep-seated breccia pipes are known to be overlain by gypsum collapse features (Wenrich and others, 1986). In the early 1980's, Uraneuz USA, Inc. from Reno, Nevada drilled several reported breccia pipes for uranium just off the northeast edge of the quadrangle, but test results are not available. No breccia pipes are mapped in The Divide quadrangle.

The Springdale Sandstone Member of the Moenave Formation, which is extensively exposed in the quadrangle, produced more than 7 million ounces (220,000 kg) of silver prior to 1900 at the Silver Reef mining district near Leeds, Utah, about 8 miles (13 km) north of the quadrangle (Proctor and Brimhall, 1986). Proctor and Shirts (1991) provide an excellent account of the discovery, disbelief, re-discovery, and development of this unusual mineral occurrence. Anomalous concentrations of silver are present in the Springdale Sandstone well beyond the boundaries of the mining district and some gold has been reported, but none of ore grade (Proctor and Brimhall, 1986). Locally, significant copper and uranium concentrations are also present in the Springdale Sandstone at Silver Reef (James and Newman, 1986) with several hundred tons of uranium ore mined beginning in 1950. In The Divide quadrangle, the sandstone is exposed in Warner Valley along the base of the cliff around the southwest edge of Sand Mountain and is repeated several times by normal faulting in east Warner Valley.

Claims have been staked for paleoplacer deposits of precious metals from the red beds of the Moenkopi Formation around the base of Little Creek Mountain. Jack Powell of Little Creek Venture staked claims in the middle red member in SW1/4 of section 12, T. 43 S., R. 13 W. and the lower red member in NE1/4 section 25, T. 43 S., R. 13 W. Master Petroleum of Bryon, Texas has reportedly staked similar claims (Larry Gore, Bureau of Land Management, verbal communication, May 27, 1999)

Oil and Natural Gas

There has been no production of oil or gas in The Divide quadrangle. The nearest production was from the Virgin oil field, which was first developed in 1907. It is 7 miles (11 km) northeast of the quadrangle, adjacent to Zion National Park. Production through 1963 was 195,000 barrels (31,000 m^3) of oil from 30 wells, although over 200 wells were drilled (Eppinger and others, 1990). Oil was derived from a sandstone and vuggy limestone interval 1 to 8 feet (0.3-2.4 m) thick in the uppermost part of the Timpoweap Member of the Triassic Moenkopi Formation, with minor production from the Pennsylvanian Callville Limestone. The brown to black oil from the Virgin field ranges from 22° to 32° API gravity, and has a mixed paraffin-asphalt base (Heylmun, 1993). The field lies in a small synclinal pocket near the axis of a broad, low-relief anticline that plunges gently northward. After erosion caused the reservoir pressure to dissipate, the oil drained from the anticline into small synclinal pockets on the nose. The accumulations were also controlled by local porosity and fracturing (Heylmun, 1993).

Of five petroleum exploration wells drilled in The Divide quadrangle, only one was located west of the Hurricane Fault. Intex Oil Skyline #1, drilled in 1960 to a total depth of 3,006 feet (917 m), is located in the NW1/4NE1/4 section 28, T. 43 S., R. 13 W. It is drilled near the center of the half-dome horst of Triassic rocks in east Warner Valley and was spudded in the middle member of the Moenkopi Formation. Drilling reportedly encountered the Toroweap Formation at 905 feet (276 m), the Coconino [Queantoweap] Sandstone at 1,425 feet (435 m), and the Pakoon Dolomite at 2,745 feet (837 m). No shows were reported. The Dawn Federal, located in the southeast corner of the quadrangle in the SW1/4SW1/4 section 31, T. 43 S., R. 12 W., was drilled in 1962 to a depth of 1,353 feet (413 m). This well was spudded in the Timpoweap Member of the Moenkopi Formation, and drilling reportedly reached the Kaibab Formation at 150 feet (46 m) and the Coconino [Queantoweap] Sandstone at 950 feet (290 m), with oil shows in the interval between 835 and 880 feet (255-268 m). The deepest well, Glen Coluas #1 drilled by KT Petroleum in 1964, is located in the NE1/4NE1/4NE1/4 section 25, T. 42 S., R. 13 W. and was drilled to a total depth of 6,260 feet (1909 m). The approximate recorded formation tops are the Coconino-Supai Sandstone at 1,170 feet (357 m), Pakoon Dolomite at 2,505 feet (764 m), Mississippian strata at 3,570 feet (1,088 m), and Devonian strata at 4,535 feet (1,383 m). The Devereax Federal #1, drilled in 1966 to a depth of 6,000 feet (1,830 m), is located near the edge of the Hurricane Cliffs in SW1/4SW1/4 section 14 T. 43 S., R. 13 W., while the Virgin Federal #3, located in the NW1/4NW1/4NW1/4 section 36, T. 42 S., R. 13 W., was drilled in 1974 to an unreported depth. All wells are plugged and abandoned.

A Hurricane Cliffs hydrocarbon tar sand deposit, as listed on the CRIB sheet for Utah state inventory of natural resources, is located between the top of the Hurricane Cliffs and the southern two basalt-capped hills of “White Face” and “The Wart” in the NE1/4 section 34, T. 42 S., R. 13 W. The location is also included in the compilation of surface and shallow oil-impregnated rocks and shallow oil fields in the United States by Ball Associates Ltd. (1965) and on Ritzma’s (1979) map of oil-impregnated rock deposits of Utah. The asphalt-like seep is in the Timpoweap Member of the Moenkopi Formation, which is the primary producing interval in the Virgin oil field (Blakey, 1974, 1977, 1979).

Geothermal Resources

The Divide quadrangle is in an area with geothermal potential (Mabey and Budding, 1985; Budding and Sommer, 1986). Quaternary basalt vents in the region, some as young as about 10,000 years, could be an indicator of geothermal potential. However, basalts are believed to ascend through relatively small pipes from depths of several miles (Budding and Sommer, 1986). The hydrothermal alteration of, and emplacement of minerals into, the Permian Harrisburg Member of the Kaibab Formation along the Virgin anticline just west of the quadrangle is perhaps another indicator of geothermal potential. No hot springs are known in the quadrangle, but hot springs are present within 4 miles (6 km) to the north. The highest recorded spring water temperature in the area is 108° F (42° C) at Pah Tempe Hot Springs between Hurricane and LaVerkin (Budding and Sommer, 1986).

WATER RESOURCES

Water is of great importance in the St. George Basin since the population is rapidly increasing and much of the area receives only 10 to 12 inches (25-30 cm) of precipitation per year (Cordova and others, 1972; Cordova, 1978; Clyde, 1987; Horrocks-Carollo Engineers, 1993; Utah Division of Water Resources, 1993). Water availability and use for the Kanab Creek/Virgin River Basin is summarized in the 1993 State Water Plan (Utah Division of Water Resources, 1993), as well as development, regulatory, and other issues that relate to water management in the area. A study by the Utah Geological Survey, the Utah Division of Water Resources, and the U.S. Geological Survey Water Resources Division evaluated major aquifers in detail (Hurlow, 1998). Only a brief overview is given here.

Surface Water

Cordova and others (1972) and Sandberg and Sultz (1985) summarized flow data on perennial streams in the area and reported on surface-water quality in the upper Virgin River basin; however, no perennial streams flow through The Divide quadrangle. Fort Pearce Wash cuts across the quadrangle near the southwest corner, before finally joining the Virgin River a few miles west of the quadrangle boundary. It has an estimated average annual flow of 2,000 acre-feet (2,613,600 m^3) but it is dry most of the year, as are Gould Wash, Frog Hollow, and Workman Wash that cut across the northeast corner of the quadrangle. Many catchment ponds have been constructed to pool runoff water, particularly on the east half of the quadrangle. A few springs create a small perennial flow down their drainages for short distances.

The east half of the proposed 960 acre (389 hectare) Sand Hollow Reservoir will flood a portion of Sand Mountain in the northwest corner of the quadrangle. It will be operated by the Washington County Water Conservancy District as an off-line reservoir with water being pumped into it during peak runoff months and then allowed to re-enter the Quail Lake system by gravity flow during the summer months. An estimated 10,000 acre-feet (13,070,000 m^3) will be utilized from the 28,000 acre-foot (36,596,000 m^3) reservoir annually, with an additional 5,000 acre-feet (6,535,000 m^3) being recovered by several down-gradient wells in the Navajo Sandstone as ground water is recharged by the reservoir (Washington County Water Conservancy District, 1997).

Ground Water

The Virgin River controls base level in the quadrangle and the unconfined potentiometric surface slopes northwest toward the river (Cordova and others, 1972; Cordova, 1978; Clyde, 1987). Important aquifers in the quadrangle are in the Chinle, Moenave, Kayenta, and Navajo Formations, and in thin unconsolidated deposits (Cordova and others, 1972; Clyde, 1987). Of these, the Navajo aquifer is the most important. Regionally, it consists of about 2,000 feet (610 m) of porous, well-sorted, fine- to medium-grained sandstone, but ground water is best transmitted through the formation along fractures (Hurlow, 1998). Only the lower 1,000 feet (305 m) of Navajo Sandstone is exposed in the northwest part of the quadrangle. Regionally, the primary recharge area for the Navajo aquifer is limited to the Navajo outcrop area (Freethey,

1993) since the overlying Temple Cap and Carmel Formations form an impervious barrier that effectively seals the Navajo from surface waters. Recharge is from precipitation on the Navajo and from streams that cross the Navajo. Wells in the Navajo aquifer north and northwest of the quadrangle are a major source of domestic water for the area (Horrocks-Carollo Engineers, 1993; Willis and Higgins, 1996). In The Divide quadrangle, the Navajo dips to the northwest, isolated as Sand Mountain. No streams cross the aquifer so the only recharge currently comes from precipitation; however, Sand Hollow Reservoir is expected to recharge the Navajo aquifer at a rate of 6 to 15 cubic feet per second (cfs) (0.18-0.45 m^3/sec.) or 4,500 to 11,000 acre-feet (5,881,000-14,377,000 m^3) annually, under full reservoir conditions. Six to ten wells down gradient from the reservoir are expected to recover 5,000 acre-feet (6,535,000 m^3) of ground water annually, which will be fed directly into the St. George City water system (Washington County Water Conservancy District, 1997).

Again, because of the northwest dip of Sand Mountain and the limited recharge area, there are virtually no springs in the northwest quadrant of the quadrangle. Springs along the contact between the upper portion of the Kayenta Formation and the Navajo Sandstone are common to the west of the quadrangle on the opposite limb of the Virgin anticline where south-flowing water "spills" over this natural threshold (Higgins and Willis, 1995). Only one named spring, Swett Spring, is in The Divide quadrangle. Located at the base of Little Creek Mountain in the SE1/4 of section 24, T. 43 S., R. 13 W., it generally flows at a rate of 0.016 cfs (0.0005 m^3) from the Virgin Limestone Member of the Moenkopi Formation. A few other minor springs provide moisture for limited areas. The spring water is primarily used for stock watering.

The water quality in many springs and wells in the quadrangle is reported in Cordova and others (1972), Cordova (1978), Clyde (1987), and Freethey (1993). In general, water is fresh and of high quality in the Navajo aquifer, but older formations generally have higher total dissolved solids ranging up to salty. Water quality in unconsolidated aquifers varies considerably depending upon local conditions.

GEOLOGIC HAZARDS

The Divide quadrangle is in a tectonically active area with several faults that could generate large earthquakes. The quadrangle contains many steep slopes with landslide and rock-fall hazards. It includes formations that contain expansive, soluble, or compactible materials and radon-producing uranium. Flash floods and debris flows are also concerns as is damage from blowing sand. There is also the possibility of volcanic hazards from both local and distant sources.

Earthquakes

The Divide quadrangle is within the Intermountain Seismic Belt and the area has experienced several historical earthquakes of magnitude 4 or greater (Christenson and Deen, 1983; Anderson and Christenson, 1989; Christenson and Nava, 1992; Hecker, 1993). Historical earthquakes have not exceeded magnitude 6.5 in southwest Utah; however, geological studies indicate that faults in the region could produce earthquakes of magnitude 7 to 7.5 (Arabasz and others, 1992). The largest historical earthquake was an estimated magnitude 6.3 event in 1902 with the epicenter about 20 miles (32 km) north-northwest of the quadrangle near the Pine Valley Mountains (Arabasz and others, 1979; Christenson and Deen, 1983). The most recent large earthquake was a magnitude 5.8 event on September 2, 1992 with the epicenter located 5 miles (8 km) west of The Divide quadrangle (Pechmann and others, 1995). Ground shaking was strongly felt in the St. George and Washington City area and caused damage as far as 95 miles (153 km) from the epicenter (Olig, 1995). Preliminary seismologic data indicate that the earthquake originated at a depth of 9 miles (15 km) and was caused by dominantly normal faulting on a north-south trending fault (Pechmann and others, 1995). Distribution of the limited aftershocks implies a west-dipping slip plane, possibly a subsurface part of the Hurricane fault (Pechmann and others, 1995). Ground accelerations in the St. George and Washington City area were not measured, so an empirical relationship (Campbell, 1987) was used to estimate a peak horizontal ground acceleration (PHA) of 0.21 *g* for the area (Black and others, 1994). Ground shaking triggered landslides that destroyed homes and utilities in Springdale, 27 miles (44 km) east of the epicenter, and caused liquefaction, lateral spreads and sand blows in poorly graded sand along the Virgin River (Black and Christenson, 1993; Black, 1994; Black and others, 1994). It also caused a change in flow of Pah Tempe Hot Springs near Hurricane (figure 1) and triggered many rock falls, at least two of which caused property damage (Black and others, 1995). No surface rupture was reported from the 1992 event (Black and Christenson, 1993). Total losses from direct damage, response costs, and lost property values approached $1 million, but this value is likely a minimum (Carey, 1995).

The Divide quadrangle is in the Uniform Building Code seismic zone 2B, an area of moderate earthquake risk with expected PHA of 0.1 to 0.2 *g* (International Conference of Building Officials, 1997; Christenson and Nava, 1992) for the entire zone without regard for proximity to the fault. Site-specific values could be much greater.

Three large fault zones in the area have documented Quaternary movement and a few smaller faults have possible Quaternary movement (Christenson and Deen, 1983; Anderson and Christenson, 1989; Hecker, 1993; Lund and Everitt, 1998). Six sites along the Utah portion of the Hurricane fault have scarps on unconsolidated deposits with the youngest sediment displaced being latest Pleistocene or early Holocene in age (Pearthree and others, 1998). The Warner Valley fault displaces unconsolidated sediment near the center of the southern portion of the quadrangle 9 feet (3 m) in a north-south trending scarp that is 1,800 feet long (545 m). The Washington fault also trends north-south about 5 miles (8 km) west of the quadrangle. It displaces 10,000- to 25,000-year-old Quaternary sediments 11.5 feet (3.5 m) in the NW1/4 of section 13, T. 43 S., R15 W. (Anderson and Christenson, 1989), as well as the 900,000-year-old (Bob Biek, Utah Geological Survey, verbal communication, January 31, 2000) Washington basalt flow about 20 feet (6 m) (Higgins, 1998). The Grand Wash, Reef Reservoir, and Gunlock faults form a zone about 22 miles (35 km) west of the quadrangle (figure 1) (Hammond, 1991; Hintze and Hammond, 1994; Hintze and others, 1994).

Future earthquakes in the area of the quadrangle could generate ground-shaking and related hazards such as surface rupture, slope failure, liquefaction, flooding, and tectonic subsidence (Christenson and Nava, 1992). Poorly consolidated soil, such as is present in parts of The Divide quadrangle, can amplify ground motions relative to sites on bedrock, thereby increasing the potential for damage. Flooding may result from failure of nearby dams; diversion or destruction of canals, aqueducts, water lines, or streams; increased ground-water discharge;

seiches (large waves) in reservoirs; or tectonic subsidence in areas of shallow ground water or around reservoirs. Movement on a fault sufficient to cause surface rupture would likely damage many structures, especially older, unreinforced masonry buildings, and may rupture underground utilities. Rock falls caused by ground shaking are of increasing concern as development encroaches on steep slopes flanked by basalt flows and resistant bedrock units.

Slope Failures

Many ridges and benches bounded by steep slopes in the quadrangle have landslide and rock-fall hazards. The stability of natural slopes is dependent on lithology, ground-water conditions, and attitude of bedding or jointing (Christenson and Deen, 1983). The most common causes of slope destabilization include loss of support at the base of the slope because of stream erosion or excavations for construction, increasing pore pressure by adding water or increasing the load, ground shaking resulting from earthquakes, or strong vibrations caused by construction.

Landslides

Slip surfaces of landslides within the quadrangle develop primarily on the middle red member of the Moenkopi Formation along the south edge of Little Creek Mountain. The landslide mass involves overlying bedrock units of the Moenkopi Formation and talus. Most large landslides in these areas probably last moved during Pleistocene time when conditions were wetter than they are today (Christenson, 1992). There is also potential for landslides to develop in the clay-rich Petrified Forest Member of the Chinle Formation that is exposed throughout much of Warner Valley. The clay absorbs moisture, forming a weak, pasty substance that is prone to slumping (Harty, 1992). Although many of these slopes are apparently stable, they may fail if material is removed from the base, or if additional water or fill is added by construction to the top of the slope.

Rock Falls

Rock falls are common in the quadrangle, as evidenced by abundant rock debris both on and at the base of steep slopes. Rock falls occur naturally when less resistant rock layers are eroded from beneath more resistant, fractured rock. They may also result from ground shaking caused by earthquakes. Human activities that artificially increase the natural slope of a hillside, introduce significant moisture to hilltops, or add substantial weight to the edge of hilltops also increase the potential for rock falls. Buildings constructed at the top of steep slopes are in danger of damage by rock falls as their foundation is undermined, whereas those constructed at the base are in danger because of potential impact.

Steep slope areas capped by basalt, Navajo Sandstone, Shinarump Conglomerate Member of the Chinle Formation, and the Kaibab and Toroweap Formations have the greatest potential for rock fall. Rock falls from the basalt-capped ridges are particularly dangerous since the basalts are dense, jointed, and form equidimensional blocks that roll well and don't break up during descent. Major rock-fall hazards involving the Kayenta Formation and Navajo Sandstone exist around the south edge of Sand Mountain, and around Little Creek Mountain, which is capped with the Shinarump Conglomerate Member of the Chinle Formation. Massive sandstone beds of the these units have intersecting joints, making it common for blocks of these rocks to detach and roll. Several blocks fell from these cliffs during the 1992 earthquake (Christenson and Nava, 1992). Also, massive limestone boulders from the Kaibab and Toroweap Formations roll down the steep face of the Hurricane Cliffs.

As the development of subdivisions and other structures continues, the probability of damage from rock falls also increases. Although a rock-fall hazard exists near the base of all slopes, site-specific investigations indicate that the local degree of hazard varies significantly and is dependent upon several variables. These include the distance of the site from the base of the slope, the nature and stability of slope debris, the local protection provided by previous rock-fall blocks, and the presence of erosional gullying in the slope which may deflect falling rocks (Christenson, 1992).

Problem Soil and Rock

Although development within the quadrangle is currently minimal, several highly publicized incidents of structural damage in the area due to problem soil and rock have increased local public awareness of such potential problems (Daily Spectrum newspaper, various issues from 1990 to 1999). Hurricane City officials, responding to the concern, now require site evaluations and laboratory reports for new subdivisions. Hazards are of three types: expansive soil and rock, soluble soil and rock, and collapsible or compressible soil.

Expansive Soil and Rock

Bentonitic clay from volcanic ash in the mudstone and shale intervals of the Petrified Forest Member of the Chinle Formation (commonly known as "blue clay"), which swells when moistened, is responsible for most of the expansive soil and rock problems in the area. Since it lies stratigraphically above the ridge-forming Shinarump Conglomerate Member, valley areas up-dip from the Shinarump are formed in these swelling clays and are usually thinly covered by sediment. In The Divide quadrangle, these valley areas are extensive and include almost all of Warner Valley. In swell tests using a 60-pounds-per-square-foot (psf) (293 kg/m^2) surcharge load, expansion greater than 12 percent is classified as critical (Rick Chesnut, Kleinfelder, verbal communication, May 28, 1998). Clay from the Petrified Forest Member is highly variable but typically swells 15 to 20 percent and some samples have tested as high as 38 percent swell. Based on Atterburg-limits test results, the clay is classified as CH soil, or a “lean to fat clay,” with a plasticity index of 15 to 30 and liquid limit of 30 to 55. Even in some tests that apply pressures of 3,000 to 5,000 pounds per square foot (14,650-24,417 kg/m^2), the clay can still swell 2 to 5 percent (Rick Chesnut, Kleinfelder, verbal communication, May 28, 1998). Thick overburden or other measures are necessary to protect a structure from this amount of swelling.

The Shnabkaib Member, which is well exposed in east Warner Valley and near the base of Little Creek Mountain, also has expansive clays. To a lesser degree, mudstone intervals in the Virgin Limestone Member and the three red members of the Moenkopi Formation, as well as the Whitmore Point Member of the Moenave Formation, can create problems due to expansion (Christenson and Deen, 1983). In addition, easily eroded, fine-grained soil with moderate swell potential (4 to 8 percent) is common on flat to very gentle slopes on flood plains, alluvial lowlands, and benches (Christenson and Deen, 1983).

Common signs of expansive soils are cracked foundations, heaving and cracking of floor slabs and walls, and failure of wastewater disposal systems (Mulvey, 1992). Even if engineering precautions are taken to protect buildings, expansive soils can damage neglected sidewalks, roads, porches, garages, driveway and patio slabs, and underground utilities. Damage can occur quickly. Thompson (1992) found an average time lapse of two years and seven months from construction to repairs in similar settings in the Denver, Colorado area.

Soluble Soil and Rock

Soluble soil and rock, deposits that contain minerals that dissolve when exposed to water, are common in the quadrangle. These include gypsiferous deposits, weathered limestone, and pedogenic and ground-water-deposited calcium carbonate (Christenson, 1992). The Shnabkaib Member, and to a lesser degree, the red members of the Moenkopi Formation and the lower portion of the Kayenta Formation, are subject to settlement, collapse, piping, and local heaving problems due to dissolution of gypsum (Christenson and Deen, 1983). Piping can also occur in the Petrified Forest Member of the Chinle Formation. Solubility tests run by Kleinfelder on the Shnabkaib Member show an average of 3 to 8 percent of the sample is dissolvable. As development continues, weathered limestone and gypsum of the Kaibab and Toroweap Formations could pose a major problem.

Pedogenic carbonates developed in terrace gravel and older geomorphic surfaces are common in the quadrangle and impede water percolation if undisturbed. However, construction may fracture the seal and increase weathering (Christenson, 1992). Honeycomb gypsum and solution cavities as much as two feet (0.6 m) wide are sometimes encountered in the area during excavation (Dave Black, Black, Miller and Associates, verbal communication, 1995).

Collapsible and Compressible Soil

Hydrocompaction, which causes subsidence, may occur in certain geologically young materials present in the quadrangle (Mulvey, 1992). Subsidence occurs in loose, dry, low-density deposits that decrease in volume or collapse when they are saturated or loaded for the first time since deposition (Costa and Baker, 1986). To measure collapsibility, a sample is weighted with 1,000 psf (4,883 kg/m^2) and then saturated with water. The percent of volume change, which averages 2 to 6 percent in the region, is then calculated (Rick Chesnut of Kleinfelder, personal communication, May 28, 1998). Debris flows deposited at the mouth of drainages during flash floods commonly contain collapsible soils. Some of these areas are currently being subdivided in The Divide quadrangle. Other low-density deposits, such as eolian silt and sand, mainly derived from the upper portion of the Kayenta Formation and the Navajo Sandstone, are commonly poorly consolidated and require compaction prior to construction.

Blowing Sand

As development continues, blowing sand may become a genuine concern in the area. Currently, blowing sand that causes the migration of sand dunes must be periodically removed from the Warner Valley road in order to keep the road passable. The development of facilities around Sand Hollow Reservoir will require special efforts to keep sand from encroaching into unwanted areas such as ball fields, camping areas, and the paved road to the off-highway vehicle (OHV) staging area.

Flooding and Debris Flows

Floods are probably the most frequent and consistently destructive natural hazard in the area. Most of the historical record of flooding published by Utah Division of Comprehensive Emergency Management (1981) was summarized by Christenson and Deen (1983). The high flood hazard results from the complex interaction of the area's rugged topography and seasonal weather patterns (Lund, 1992). Flooding within the quadrangle is influenced by snow melt and storms in the region. Although the conditions that cause flooding are not controllable, the relative hazard posed by flooding is generally manageable with wise planning that would encourage preservation of natural flood plains and discourage man-made channelization and development within the 100-year flood plain.

Fort Pearce Wash and its tributaries provide drainage for the south portion of The Divide quadrangle, while Gould Wash and its tributaries drain the northeast portion. Any water on Sand Mountain usually doesn't flow very far northward, but may flow into Sand Hollow Reservoir. More locally, levees and dams were built on many smaller drainages to inhibit flooding of farmland and Hurricane City; however, most of these structures are not designed to adequately provide protection for subdivisions or more extensive development.

Debris flows are poorly sorted masses of clay- to boulder-sized materials that flow in a muddy slurry. They generally develop during or after a period of unusually high precipitation as colluvium and other loose deposits become saturated with water and begin to flow. They are a concern in gullies and washes and in some areas near moderate and steep slopes in many parts of the quadrangle. Development along the base of the Hurricane Cliffs increases the potential damage from debris flows on alluvial fans as runoff drains the area above the cliffs after a storm.

Radon

Radon gas forms as a product of three different radioactive decay series, but is derived primarily from the decay of uranium-238 (Solomon, 1992a). Alpha particles, emitted by atoms as they decay, are the main danger. Outside the body, alpha particles pose no danger because they cannot penetrate the skin. If radon gas is inhaled, however, these particles can cause serious damage to sensitive cells, eventually causing lung cancer (Wilbraham and others, 1990). The U.S. Environmental Protection Agency estimated that 8,000 to 40,000 Americans die each year from lung cancer caused by long-term radon inhalation (Schmidt and others, 1990).

Radon can enter homes and offices built on soil and rock rich in uranium through porous building materials, cracks in basement floors, walls or slabs, or other openings below grade. If the home is well insulated, the gas may be trapped inside and inhaled by the occupants. Because radon gas is colorless, odorless, and causes no pain when it is inhaled, most people are never aware of its presence.

Indoor-radon levels measured in the southern St. George basin during a 1988 statewide survey conducted by the Utah Division of Radiation Control (UDRC) indicated local high radon levels (Sprinkel and Solomon, 1990). A map of potential radon hazards in Utah shows The Divide quadrangle area as having a moderate radon-hazard potential which could result in an indoor radon concentration of 4 to 10 picocuries per liter (pCi/L) of air (Sprinkel, 1987; Solomon, 1992a), well above the action level of 4 pCi/L specified by the U.S. Environmental

Protection Agency and U.S. Department of Health and Human Services (1986). Above this level, hazard-reduction procedures are recommended. The average ambient outdoor radon level is 0.2 pCi/L (Monroe and Wicander,1998).

The primary geologic prerequisite for elevated indoor-radon levels is uranium in the soil around building foundations. Solomon (1992b) measured uranium levels in the southern St. George basin using gamma-ray spectrometry and found that high uranium levels originate from three distinct sources. A local primary source where levels were highest (up to 6.7 parts per million [ppm]) is the tuffaceous, fine-grained rock and residual bentonitic soil of the Petrified Forest Member of the Chinle Formation, which is extensively exposed in The Divide quadrangle. Levels were also high (up to 3.4 ppm) in granular soils of the Virgin River flood plain, which are derived in part from Miocene intrusive igneous rocks eroded from the Pine Valley Mountains to the north and which are of little concern in The Divide quadrangle (Cook, 1957). Secondary uranium mobilization, suggested by high uranium/thorium ratios, has resulted in uranium enrichment in local areas of rock and soil.

Two important geologic factors inhibit the ability of radon to migrate into buildings: shallow ground-water levels, since pore water effectively traps radon, and impermeable soil, since there must be soil pathways through which the gas can migrate. Solomon (1992b) contoured a map of the southern St. George basin showing depth to ground water using well data from Cordova and others (1972), and a map of soil permeability using data from a soil survey made by Mortensen and others (1977). He then used a combination of all three factors (uranium concentration, ground-water level, and soil permeability) to derive a map showing the relative potential for elevated indoor-radon levels in the southern St. George basin.

Solomon's map, which ends just west of The Divide quadrangle, indicated the most extensive areas of high-hazard potential are in the small hills underlain by the Petrified Forest Member of the Chinle Formation and in the alluvial deposits of the Virgin River flood plain. The factor common to areas of high-hazard potential is a uranium level greater than 3 ppm. Permeability varies considerably in these areas, from relatively high in the flood plain to relatively low in the shale of the Petrified Forest Member, but ground water is nowhere less than 10 feet (3 m) deep (Solomon, 1992b). The area of the Washington Dome quadrangle that was included in his study was of moderate radon-hazard potential.

Because of the many non-geologic factors that influence indoor-radon levels, a quantitative relationship between geologic factors and indoor-radon levels does not exist. However, the relative hazard potential can be used to prioritize indoor testing and to evaluate the need for radon-resistant new construction (Solomon, 1996).

Volcanism

Volcanic hazards in the area are of two main types: ash and lava flows from local sources, and wind-blown ash and dust from distant sources (Mabey, 1985; Bugden, 1992). Only hazards from local sources are discussed here. Volcanic activity in southwest Utah during mid-Cenozoic time was characterized by violent eruptions of large volumes of felsic pyroclastic material, but late Cenozoic eruptions resulted in smaller, mafic cinder cones and flood basalts. The most recent basalt flow in the area, the Santa Clara flow, is 15 miles (24 km) west of the quadrangle. Luedke and Smith (1978) indicated this flow is less than 1,000 years old. However, Willis and Higgins (1996) believe it is 10,000 to 20,000 years old based on downcutting next to the flow and weathering of the basalt. Such relatively young flows and geothermal activity suggests that additional eruptions will occur. Future eruptions can be expected to follow a similar pattern, producing relatively small cinder cones and slow-moving flows that follow topographic lows. It is likely that flows from future eruptions would follow drainages into populated areas. Eruptions would likely be preceded by earthquake swarms which could provide some advance notice of an impending eruption. Hazards from future eruptions include damage and injuries from molten lava, explosively ejected cinders and volcanic gas, blockage of transportation corridors and rivers, disruption of utilities, and fires (Mabey, 1985).

SCENIC AND RECREATIONAL RESOURCES

The Divide quadrangle is in the "red rock" country of southwest Utah and is surrounded by buttes and mesas of red sandstone. Many are capped by black basalt, creating a striking visual contrast. The quadrangle is also near the lowest elevation in the state and has the warmest climate. The combination of the striking scenery and warm climate make the area a popular recreation and retirement destination. It is near several popular recreation sites, including Snow Canyon State Park and Zion National Park.

Sand Mountain is the most popular area for year-round off-highway vehicle (OHV) use in Washington County. The sand dunes are low, rounded hills that provide a challenge for novice to intermediate riders. Additionally, a popular January event sponsored by Wasatch Trials Association annually draws OHV enthusiasts from several western states. As Sand Hollow Reservoir is constructed, water-based recreation, such as boating and fishing will become available within the quadrangle. Proposed recreation facilities associated with Sand Hollow Reservoir include three camping areas, one group picnic activity area, a day use parking area, a marina flanked by two beaches, and a paved road to a OHV staging area. Views of Pine Valley Mountains and the Virgin anticline to the north and the cliffs of Zion National Park to the east from this area are stunning.

Dinosaur footprints and trackways, located near the west edge of the quadrangle in Warner Valley in the NW corner of section 30, T. 43 S., R. 13 W, were discovered in May, 1982, by Gary Delsignore of Cedar City. At that time 161 separate prints representing 23 trackways were documented belonging to *Grallator*, a coelurosaurid, and *Eubrontes*, a possible plateosaurid (Miller and others, 1989). They are actually within the lower portion of the Kayenta Formation, although the interpretive sign put up by the Bureau of Land Management (BLM) states that they are in the Moenave Formation. The BLM placed a metal diversion structure in the wash to keep runoff and debris from destroying or covering a portion of the tracks.

History enthusiasts enjoy following the route of the historical Honeymoon Trail, which crosses the quadrangle and which was used extensively by couples coming from settlements in Arizona to be married in the St. George Temple. This trail traverses the southern portion of the quadrangle, winding down off of the Hurricane Cliffs just to the south of the quadrangle boundary and then continuing west through Warner Valley. Views in all directions from the top of the Hurricane Cliffs are captivating.

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FIGURE CAPTIONS

Figure 1. Location of The Divide and surrounding 7.5' quadrangles, with major geographic and geologic features; basalt flows are shaded. MVW = Mountain Valley Wash, VRG = Virgin River Gorge, TC = Timpoweap canyon, and PT = Pah Tempe Hot Springs.

Figure 2. Oblique aerial view northeast to the Hurricane Cliffs, which are eroded from the Early Permian Queantoweap, Toroweap, and Kaibab Formations. The Early Triassic Moenkopi Formation forms Little Creek Mountain, which is capped by the Shinarump Conglomerate Member of the Late Triassic Chinle Formation. Both cinder cones of The Divide flow are visible in the middle left side of the photo.

Figure 3. Strata in The Divide quadrangle and their relationship with sea level fluctuations. Vail and others (1977) divided the interval represented by strata exposed in the quadrangle into eight second-order supercycles, five of which are found within the quadrangle. The St. George area underwent erosion and/or sediment bypass during three of the second-order sequences, so sea-level fluctuations during the Late Permian, Middle Triassic, and earliest Jurassic (shown by the sea level curve) are not represented by rock in the quadrangle. The five documented second-order cycles are further divided into nine third-order cycles that reflect smaller relative changes in sea level. Systems tracts are listed for the third- and fourth-order cycles. Modified from Vail and others (1977), Hintze (1993), and Dubiel (1994). Time scale from Palmer and Geissman (1999). Vertical scale is based on time of deposition, not on strata thickness.

Figure 4. Photo looking northeast at the contact between the undulating layers of the Harrisburg Member of the Kaibab Formation, below, and the straight layers of the Timpoweap Member of the Moenkopi Formation, above, in the NE1/4NE1/4 of section 10, T. 43 S., R. 13 W. Note the northernmost cinder cone of The Divide flow that caps the ridge.

Figure 5. (A) The second-order sequence of the Moenkopi Formation is divided into three third-order sequences indicating three smaller transgressive-regressive sequences. (B) Similarly, the third-order sequence of the Virgin Limestone and middle red member is divided into three fourth-order sequences with transgressive system tracts (TST) of the limestone ledges separated from the muddy siltstone interbeds of the highstand systems tract (HST) by a maximum flooding surface (MFS). (C) Each limestone ledge is itself a fifth-order parasequence. The lower portion of each ledge is finer, more muddy, and non-fossiliferous, signifying a transgressive systems tract (TST), while the upper portion is a coarser wackstone with birdseye structures and fossils, signifying a highstand system tract (HST). The two portions are divided by one inch (2.5 cm) or less of dark-grayish-brown shale, indicative of a maximum flooding surface. Modified from Vail and others (1977), Hintze (1993), Dubiel (1994), and additional work in this project.

Figure 6. Geochemical classification of basaltic rocks in The Divide quadrangle using the scheme of Le Bas and others (1986). See appendix for analytical data. Qbr = Remnants flow, Qbd = Divide flow, Qbgw = Gould Wash flow, and Qbg = Grass Valley flow.

Figure 7. The Divide flow cascade over the Hurricane Cliffs in the SW1/4SE1/4 of section 3, T. 43 S., R. 13 W. Photo looking northeast.

Figure 8. Photo looking east at Permian rocks of the Hurricane Cliffs capped by the Remnants flow, which sits on the lower red member of the Moenkopi Formation (sections 27 and 28, T. 42 S., R. 13 W.). The portion of the Remnants flow in the valley is partly buried by alluvial-fan deposits shed from the cliffs.

Figure 9. Photo looking southwest from the SW1/4, section 23, T. 43 S., R 13 W. on the Hurricane Cliffs down into east Warner Valley. The Kayenta Formation that forms “Noah’s Ark” is separated from that of Sand Mountain farther west by the Warner Valley dome, the pod-shaped horst of Triassic rocks in the valley.

Figure 10. The main trace of the Hurricane fault trends between the gray Permian rocks that form the Hurricane Cliffs and the Jurassic Kayenta Formation that forms “Noah’s Ark.” Photo taken looking north from SE1/4NE1/4 section 34, T. 43 S., R. 13 W. Note the Grass Valley flow and cinder cone in the middle left and the Pine Valley Mountains in the background. The basalt cascade of The Divide flow is visible atop the Hurricane Cliffs in the distance.

Appendix

Geochemical analyses of basalt flows in The Divide quadrangle

THE DIVIDE (Qbd)							
FLOW SAMPLE	VR4107	TD11699-11	TD11699-12	TD11699-13	TD12999-1	TD12999-2	TD12999-3
long (^{0}W)	113.28	113.27	113.275	113.286	113.298	113.298	113.282
lat (^{0}N)	37.087	37.058	37.059	37.064	37.072	37.072	37.083
	X-ray Fluorescence Analyses, wt. %						
Al_2O_3	10.99	10.53	10.67	11.27	11.32	11.13	10.92
CaO	10.77	10.85	10.73	11.12	10.87	11	10.82
Cr_2O_3	0.03	0.07	0.06	0.05	0.06	0.06	0.05
Fe_2O_3	13.35	13.23	13.22	12.97	12.94	12.95	13.21
K_2O	1.74	1.37	1.41	1.39	1.37	1.46	1.38
MgO	12.27	12.7	12.51	11.61	11.79	11.71	11.75
MnO	0.19	0.18	0.19	0.19	0.18	0.18	0.18
Na_2O	2.7	2.69	2.77	2.96	3.08	2.91	2.76
P_2O_5	0.78	0.74	0.75	0.78	0.81	0.77	0.79
SiO_2	43.62	43.97	43.7	43.96	44.12	44.05	44.77
TiO_2	2.6	2.51	2.49	2.51	2.45	2.49	2.59
	Icp-MS, ppm						
Total	99.05	98.88	98.5	98.81	98.99	98.71	99.24
Ba	715	682	670	735	707	708	672
Ce		106.5	109	110	112	113	110
Cs	1	0.3	0.3	0.3	0.4	0.4	0.5
Co		59	60	54.5	56	57	57
Cu		80	80	75	75	80	75
Dy		6.2	6.1	6.3	6.1	6.2	5.9
Er		2.6	2.6	2.8	2.7	2.8	2.8
Eu		2.8	3.1	2.7	2.9	3	3.3
Gd		9.4	9.9	9.4	9.2	9.5	9.1
Ga		19	20	19	19	20	19
Hf	6	6	6	6	6	6	7
Ho		1	1.1	1.1	1.1	1.1	1
La	55	53.5	57.5	57.5	58	58	56.5
Pb		20	25	25	15	15	15
Lu		0.3	0.3	0.3	0.3	0.3	0.3
Nd		50	51.5	51.5	52.5	53.5	52
Ni		335	280	280	310	300	310
Nb	69	59	60	60	62	62	62
Pr		12.2	13.1	13.1	13.1	13.1	12.8
Rb		17.4	18	18	18.4	18.4	18.2
Sm	20	10.3	10	10	10	9.8	10.2
Ag		1	1	1	1	1	1
Sr	846	772	797	797	790	810	786
Ta	7	3.5	3.5	3.5	4	4	4
Tb		1.2	1.2	1.2	1.3	1.3	1.3
Tl		<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Th		7	8	8	8	8	8
Tm		0.4	0.3	0.3	0.3	0.4	0.3
Sn		2	2	2	1	2	2
W		<1	<1	<1	<1	<1	<1
U		2	2	2	2	2	2
V		270	270	270	275	290	270
Yb		2.1	2.2	2.3	2.2	2.4	2.3
Y	27	26	26	26	26.5	27	26.5
Zn		130	125	120	120	130	120
Zr	219	236	237	237	239	243	255

GRASS VALLEY (Qbg)						
Flow Sample	TD11699-5	TD11699-6	TD11699-7	TD11699-8	TD11699-9	TD11699-10
long (^{0}W)	113.319	113.33	113.318	113.311	113.316	113.308
lat (^{0}N)	37.095	37.085	37.082	37.085	37.074	37.063
	X-ray Fluorescence Analyses, wt. %					
Al_2O_3	15.91	15.73	15.63	15.94	15.71	15.33
CaO	8.12	9.05	8.87	9.09	8.93	9.07
Cr_2O_3	0.03	0.03	0.01	0.01	0.01	0.03
Fe_2O_3	10.46	10.1	10.15	10.11	10.07	10.22
K_2O	1.53	1.36	1.42	1.4	1.29	1.34
MgO	7.7	8.04	8.12	7.85	8.25	8.21
MnO	0.16	0.16	0.16	0.16	0.16	0.16
Na_2O	4.1	3.53	3.89	3.73	3.64	3.58
P_2O_5	0.6	0.55	0.56	0.56	0.54	0.54
SiO_2	48.31	48.44	48.01	47.81	48.23	48.28
TiO_2	1.9	1.75	1.73	1.7	1.76	1.7
Total	98.82	98.89	98.55	98.79	99.34	98.46
Ba	426	487	468	480	475	469
Ce	69.5	70	71	69	71	68
Cs	0.1	0.1	0.3	0.1	0.1	0.1
Co	36.5	39.5	39.5	42.5	41	37.5
Cu	50	55	55	60	65	55
Dy	5.2	5.5	5.4	5.5	5.1	5.1
Er	3	3.2	3	3	2.9	3.2
Eu	2.1	2.2	1.9	1.9	2.1	1.9
Gd	6.6	6.8	6.4	6.4	6.6	6.2
Ga	17	18	18	18	14	18
Hf	6	5	6	6	5	5
Ho	1	1.1	1.1	1	1.1	1.1
La	34	35	35.5	35.5	35	34
Pb	30	15	5	15	5	25
Lu	0.4	0.4	0.5	0.4	0.4	0.4
Nd	34	34.5	34.5	33	35	32.5
Ni	90	135	115	120	145	125
Nb	25	24	24	23	21	23
Pr	8.2	8.2	8.2	8.4	8.7	7.8
Rb	11.4	12.8	13.4	11.4	13.4	12.8
Sm	6.3	6.5	6.6	6	7	6.5
Ag	<1	<1	<1	<1	1	<1
Sr	734	690	675	667	719	668
Ta	1.5	1.5	1.5	1.5	1.5	1.5
Tb	1	1	1	0.9	1	1
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Th	3	4	4	3	5	3
Tm	0.4	0.4	0.4	0.4	0.4	0.4
Sm	2	1	1	1	<1	1
W	<1	<1	<1	<1	<1	<1
U	0.5	0.5	1	1	1	1
V	175	205	200	200	185	185
Yb	2.7	2.8	2.9	2.8	2.7	2.8
Y	26.5	26.5	26.5	26.5	26.5	26
Zn	80	85	80	80	105	85
Zr	255	283	246	231	241	236

REMNANTS (Qbr)						
Flow Sample	TD11699-1	TD11699-2	TD11699-3	TD1699-4	TD11699-1	TD50699-1
long (^{0}W)	113.306	113.308	113.326	113.317	113.297	113.294
lat (^{0}N)	37.119	37.118	37.105	37.104	37.11	37.104
	X-ray Fluorescence Analyses, wt. %					
Al_2O_3	11.75	11.91	11.86	11.94	11.57	11.54
CaO	12.76	12.5	12.55	12.29	12.57	12.48
Cr_2O_3	0.07	0.1	0.07	0.09	0.07	0.05
Fe_2O_3	11.95	11.93	11.63	11.88	12.06	12.08
K_2O	1.23	1.1	0.86	0.86	1.03	1.15
MgO	12.95	12.51	12.05	12.56	13.67	13.85
MnO	0.19	0.19	0.19	0.2	0.19	0.19
Na_2O	3.14	3.22	3.35	3.23	3.06	2.9
P_2O_5	1.07	1.05	1.08	1.04	1.06	1.04
SiO_2	41.79	42.4	42.6	42.71	42.01	42
TiO_2	1.81	1.81	1.78	1.82	1.82	1.81
Total	98.79	98.9	98.7	98.69	99.14	99.17
	ICP-MS, ppm					
Ba	1915	1880	1910	1905	2100	2140
Ce	193.5	194.5	189	195.5	202	198.5
Cs	0.6	0.5	0.7	0.7	0.7	0.6
Co	50.5	51.5	48.5	49.5	51.5	55.5
Cu	80	85	100	80	80	95
Dy	5.6	5.4	5.4	5.8	5.8	6.2
Er	2.5	2.6	2.7	2.4	2.6	2.7
Eu	3.2	3.5	3.2	3.2	3.5	3.6
Gd	10	10.4	9.8	10.1	10.3	10.2
Ga	18	18	18	18	18	15
Hf	5	5	5	5	5	5
Ho	1.1	1.1	1	1	1	1
La	107.5	106	105	107.5	111	109
Pb	30	30	25	20	15	30
Lu	0.4	0.4	0.4	0.4	0.4	0.4
Nd						
Ni	260	245	260	240	260	310
Nb	85	82	77	81	82	81
Pr	21	21	20.1	21	21.9	23.1
Rb	16	10.8	6.8	9	14.8	15.1
Sm	12.9	12.3	11.5	12.5	13	14.1
Ag	3	2	2	2	1	3
Sr	1275	1640	1140	1170	1160	1295
Ta	4.5	4.5	4.5	4.5	4.5	4.5
Tb	1.3	1.3	1.3	1.3	1.3	1.3
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Th	22	18	18	18	21	12
Tm	0.4	0.4	0.3	0.4	0.4	0.4
Sn	1	1	1	1	1	<1
W	2	1	1	<1	<1	1
U	4.5	4	4	5	5	5.5
V	290	300	280	300	300	275
Yb	2.2	2.4	2.2	2.3	2.3	2.2
Y	27	26.5	25	25.5	25.5	26.5
Zn	110	120	115	105	105	160
Zr	212	218	208	209	209	239

GOULD WASH (Qbgw)	
Flow Sample	VR-710-3
long (^{0}W)	113.264
lat (^{0}N)	37.12
X-ray Fluorescence Analysis, wt. %	
Al_2O_3	13.35
CaO	10.61
Cr_2O_3	0.04
Fe_2O_3	11.93
K_2O	0.93
MgO	10.13
MnO	0.17
Na_2O	2.99
P_2O_5	0.5
SiO_2	46.9
TiO_2	1.67
Total	99.82
ICP-MS, ppm	
Ba	696
Cs	0.1
Hf	3
La	43
Nb	36
Rb	11
Sr	669
Ta	3
Y	23
Zr	145

Description of Map Units

QUATERNARY

Alluvial deposits

Qal_{1-2} **Stream deposits** -- Moderately to well-sorted clay to fine gravel deposits in large active drainages. Qal_1 includes terraces up to 10 feet (3 m) above active channels and is 0 to 10 feet (0-3 m) thick. Qal_2 includes deposits adjacent to and dissected by Qal_1; upper surface up to 30 feet (9 m) above active channels; 0 to 20 feet (0-6 m) thick.

Qat_3 **Stream-terrace deposits** -- Well-rounded, pebble- to cobble- size clasts in a muddy to coarse sand matrix; form a poorly sorted, indurated, pedogenic carbonate-cemented conglomerate; upper surface 30 to 90 feet (9-27 m) above active channels; typically 0 to 40 feet (0-12 m) thick.

Qafy **Younger alluvial-fan deposits** -- Poorly to moderately sorted boulder- to clay-size sediment deposited at the base of the Hurricane Cliffs and locally at the mouths of active drainages; 0 to about 50 feet (0-15 m) thick.

Qafo **Older alluvial-fan deposits --** Poorly to moderately sorted boulder- to clay-size sediment deposited at the base of the Hurricane Cliffs that forms deeply dissected surfaces; 0 to about 50 feet (0-15 m) thick.

Artificial deposits

Qf **Artificial-fill deposits** -- Engineered fill and general borrow material used to create small dams; thickness variable.

Colluvial deposits

Qc **Colluvial deposits** -- Poorly sorted, angular to rounded blocks in a muddy to sandy matrix, deposited by sheet wash and soil creep on moderate slopes; only larger deposits mapped; locally includes eolian, talus, debris-flow and alluvial deposits too small to map separately; 0 to 20 feet (0-6 m) thick.

Eolian deposits

Qes **Eolian-sand deposits** -- Well- to very well-sorted, very fine- to medium-grained, well-rounded, usually frosted, mostly quartz sand; derived primarily from the Navajo and Kayenta Formations; commonly deposited in irregular hummocky mounds on the lee side of ridges, as well as on Sand Mountain and in Warner Valley; locally forms poorly developed dunes; 0 to 50 feet (0-15 m) thick.

Qed **Eolian-dune-sand deposits** -- Well- to very well-sorted, very fine- to medium-grained, well-rounded, usually frosted, mostly quartz sand blown in to dune form on Sand Mountain; derived primarily from the Navajo Sandstone; 0 to 40 feet (0-12 m) thick.

Qeo **Caliche and eolian-sand deposits** -- Well-developed soil carbonate (caliche) (Stage IV of Birkeland and others, 1991) with lesser eolian sand; generally forms planar surfaces on top of the surrounding Navajo Sandstone that are covered with nodular caliche and sparse eolian sand; 0 to 10 feet (0-3 m) thick.

Mass-movement deposits

Qmt **Talus deposits** -- Very poorly sorted, angular boulders with minor fine-grained interstitial materials; deposited on and at the base of steep slopes; 0 to 20 feet (0-6 m) thick.

Qms **Landslide deposits** -- Very poorly sorted clay- to boulder-size, locally derived debris in chaotic, hummocky mounds; located on steep slopes of Little Creek Mountain beneath the Shinarump Conglomerate, with basal detachments in the middle red member of the Moenkopi Formation; thickness highly variable.

Mixed-Environment deposits

Qae **Mixed alluvial and eolian deposits** -- Moderately to well-sorted, clay- to sand-sized alluvial sediment that locally includes abundant eolian sand and minor alluvial gravel; minor pedogenic carbonate development; mapped in small valleys east of the Hurricane Cliffs and in Grass Valley; 0 to 30 feet (0-9 m) thick.

Qea **Mixed eolian and alluvial deposits** -- Well-sorted eolian sand with minor clay- to gravel-size alluvial sediment; locally reworked by alluvial processes; 0 to 20 feet (0-6 m) thick.

Qac, Qaco

Mixed alluvial and colluvial deposits -- Poorly to moderately sorted clay- to boulder-size sediment in minor drainages; gradational with colluvial deposits; Qac deposits are in active drainages and Qaco deposits are dissected by active drainages; includes minor terraces too small to map separately; 0 to 10 feet (0-3 m) thick.

Stacked-unit deposits
(Qec/Qbgw, Qec/Qbd, Qec/Qbi, Qec/Qbr, Qec/Qbg)

Eolian sand and pedogenic carbonate over basalt flows -- Veneer of eolian sand and pedogenic carbonate that partly conceals basaltic flows; generally less than 3 feet (1 m) thick.

Basaltic flows

Qbgw **Gould Wash flow** -- Dark-gray, very fine-grained olivine basalt (Qbgw); abundant olivine phenocrysts; generally 20 to 30 feet (6-9 m) thick; yielded an $^{40}Ar/^{39}Ar$ age of 0.278 $\pm$ 0.018 Ma (Downing, 2000); originated at cinder cone to the east in the Little Creek Mountain quadrangle.

Qbd, Qbdc

The Divide flow and cinder cones -- Dark-gray, very fined-grained olivine basalt (basanite) (Qbd); cascaded over Hurricane Cliffs; north-trending dike in the SW1/4 section 12, T. 43 S., R. 13 W. may have been a partial source of flow; yielded an $^{40}Ar/^{39}Ar$ age of 0.41 $\pm$ 0.08 Ma; Qbdc denotes two partially eroded cinder cones.

Qbi **Ivan's Knoll flow** -- Medium-gray, fine- to medium-grained olivine basalt (Qbi); olivine phenocrysts up to about 0.1 inch (3 mm) across; forms highland along northwest edge of quadrangle; originated from vent to north in the Hurricane quadrangle; 15 to 25 feet (5-8 m) thick; yielded $^{40}Ar/^{39}Ar$ ages of 1.03 $\pm$ 0.02 Ma and 0.97 $\pm$ 0.07 Ma (Bob Biek, Utah Geological Survey, verbal communication, January 31, 2000).

Qbr **Remnants flow** -- Dark-brownish-black to dark-gray, medium-grained olivine basalt (basanite); remnant of deeply eroded cinder cone present near the "Three Brothers;" displaced by the Hurricane fault, and it is deeply eroded on footwall and partially buried on hanging wall; approximately 40 feet (12 m) thick; yielded $^{40}Ar/^{39}Ar$ ages of 1.06 $\pm$ 0.03 Ma and 0.94 $\pm$ 0.04 Ma (Bob Biek, Utah Geological Survey, verbal communication, January 31, 2000).

Qbg, Qbgc

Grass Valley flow and cinder cone -- Very dark-gray, fine- to medium-grained olivine basalt (Qbg); yielded an $^{40}Ar/^{39}Ar$ age of 1.47 $\pm$ 0.34 Ma (Bill Lund, Utah Geological Survey, written communication, July 14, 2000); partially eroded cinder cone (Qbgc) has 10-foot-thick (3 m) lava lake and two, 10-foot-wide (3 m) dikes that radiate from the center.

unconformity

JURASSIC

Jn **Navajo Sandstone** -- Pale to moderate-reddish-brown, cross-bedded, poorly to moderately well-cemented, well-rounded, fine- to medium-grained, frosted quartz sandstone; strongly jointed, forms cliff; basal transition zone characterized by very thick-bedded, resistant, cross-bedded sandstone layers separated by planar-bedded, silty, fine-grained sandstone with thin mudstone interbeds that display wavy bedding, dark flaser-like laminae, soft-sediment deformation features, and bioturbation. About 2,000 feet (610 m) thick but only basal 1,000 feet (305 m) exposed in the quadrangle.

Jk **Kayenta Formation** -- **I**nterbedded moderate-reddish-brown siltstone, light-purplish-red to pale-reddish-brown mudstone, and pale-reddish-brown to pale-red, fine-grained, planar-bedded, calcareous, slightly mottled sandstone; includes a few thin dolomite layers, punky gypsum intervals, and prominent ledges and cliffs near the top; dinosaur footprints in Warner Valley near base; 900 feet (273 m) thick.

Moenave Formation

Jm Moenave Formation, undivided – Shown on cross section only.

Jms **Springdale Sandstone Member --** Pale-reddish-brown to grayish-yellow, fine- to medium-grained, medium- to very thick-bedded, cross-bedded sandstone with minor, thin, discontinuous lenses of intraformational conglomerate and interbedded light-purple-gray siltstone near the middle; petrified wood is locally abundant; weathers to pale-pink, pinkish gray, and pale-reddish-purple rounded ledges; 120 feet (36 m) thick.

Jmw **Whitmore Point Member** -- Pale-red-purple to greenish-gray claystone interbedded with pale-brown to pale-red, thin-bedded siltstone with several 2- to 6-inch-thick (5-15 cm) beds of light-greenish-gray dolomitic limestone that contain algal structures and fossil fish scales of *Semionotus kanabensis* (Hesse, 1935; Schaeffer and Dunkle, 1950); nonresistant but locally well exposed; about 80 feet (24 m) thick.

Jmd **Dinosaur Canyon Member** -- Interbedded moderate-reddish-brown siltstone and very fine-grained, thin-bedded, pale-reddish-brown to grayish-red sandstone and mudstone; planar, low-angle, and ripple cross-stratification are common; forms ledgy slopes; 200 feet (61 m) thick.

unconformity

TRIASSIC

Chinle Formation

TRcp **Petrified Forest Member** -- Light-brownish-gray to grayish-red-purple bentonitic shale and siltstone with several lenticular interbeds of pale-yellowish-brown, cross-bedded, thick-bedded, resistant sandstone up to 10 feet (3 m) thick; petrified wood is common; shales weather to a "popcorn" surface with abundant mudcracks due to swelling and shrinking of bentonitic clay; forms valley; estimated to be 600 feet (185 m) thick.

unconformity ?

TRcs **Shinarump Conglomerate Member** -- Varies from a grayish-orange to moderate-yellowish-brown, medium- to coarse-grained sandstone, with locally well-developed limonite bands ("picture rock" or "landscape stone"), to a moderate-brown, chert-pebble conglomerate; contains poorly preserved petrified wood fragments; forms a dark-brown to moderate-yellowish-brown caprock above the Moenkopi Formation; variable in composition and thickness because of deposition in a braided-stream environment; 75 to 165 feet (23-49 m) thick.

unconformity

Moenkopi Formation

TRm **Moenkopi Formation, undivided** – Mapped in fault slivers along the Hurricane fault zone.

TRmu **Upper red member** -- Moderate-reddish-brown, thin-bedded siltstone and very fine-grained sandstone with some thin gypsum beds and abundant discordant gypsum stringers; ripple marks common in the siltstone; forms a steep slope with a few sandstone ledges; locally includes 20-foot-thick (6 m), fine-grained, resistant sandstone near base; 425 feet (129 m) thick.

TRms **Shnabkaib Member** -- Light-gray to pale-red, gypsiferous siltstone with several thin interbeds of dolomitic limestone near the base; upper portion is very gypsiferous and weathers to a powdery soil; forms ledge-slope topography with “bacon-stripe” appearance; 375 feet (114 m) thick.

TRmm **Middle red member** -- Interbedded moderate-red to moderate-reddish-brown siltstone, mudstone, and thin-bedded, very fine-grained sandstone with thin interbeds and veinlets of greenish-gray to white gypsum; forms slope with several ledge-forming gypsum beds near base; 360 feet (109 m) thick.

TRmv **Virgin Limestone Member** -- Three distinct medium-gray to yellowish-brown marine limestone ledges interbedded with nonresistant, moderate-yellowish-brown, muddy siltstone, pale-reddish-brown sandstone, and light-gray to grayish-orange-pink gypsum; limestone beds are usually 5 to 10 feet (1.5-3 m) thick and contain five-sided crinoid columnals and *Composita* brachiopods; total thickness is generally 75 feet (23 m).

TRml **Lower red member** -- Interbedded, slope-forming, moderate-reddish-brown siltstone, mudstone, and fine-grained, slope-forming sandstone; generally calcareous and has interbeds and stringers of gypsum; ripple marks and small-scale cross-beds are common in the siltstone; 200 feet (61 m) thick.

TRmt **Timpoweap Member** -- Lower part is light-gray to grayish-orange, thin- to thick-bedded limestone and cherty limestone; weathers to a light-brown meringue-like surface due to blebs of chert; contains few ammonites, gastropods, and brachiopods, and uncommon euhedral pyrite crystals up to 1/4 inch (1 cm) across. Upper part is grayish-orange, thin- to thick-bedded, slightly calcareous, very fine-grained sandstone with thin-bedded siltstone and mudstone intervals; weathers yellowish-brown. Forms a coherent ledge or low cliff; thickness varies from 50 to 125 feet (15-37 m).

TRmr **Rock Canyon Conglomerate Member** -- Yellowish-gray to light-olive-gray, clast-supported, but grading upward to a matrix-supported, conglomerate with pebble- and cobble-size clasts; basal part contains angular to subangular limestone rip-up clasts and brecciated blocks from Harrisburg Member of the Kaibab Formation, locally cemented with sparry calcite; rounding increases upward to subrounded, mostly chert clasts near top; thick, locally lenticular bedding; forms cliff and fills paleocanyons eroded into the Harrisburg Member; 0 to 130 feet (0-39 m) thick.

unconformity

PERMIAN

Kaibab Formation

Pkh **Harrisburg Member** -- Light-gray, fossiliferous, sandy, fine- to medium-grained limestone interbedded with red and gray gypsiferous siltstone, sandstone, and gray gypsum beds several feet thick; beds of cherty limestone, sandy limestone, and chert about 30 feet (9 m) thick form resistant low cliff near middle; beds locally distorted due to dissolution of interbedded gypsum; forms slope with limestone ledges; thickness varies greatly due to erosion associated with the Permian-Triassic unconformity; 30 to 175 feet (9-53 m) thick.

Pkf **Fossil Mountain Member** -- Yellowish-gray, abundantly fossiliferous, cherty limestone that forms a prominent cliff; silicified fossils include corals, brachiopods, crinoids, and bryozoans; reddish-brown and black chert forms irregularly bedded nodules and causes the outcrop to appear black-banded; 300 feet (91 m) thick.

unconformity

Toroweap Formation

Ptw **Woods Ranch Member** -- Grayish-pink to very-pale-orange, very thick-bedded gypsum with interbeds of light-brownish-gray siltstone, pale-red shale, and yellowish-gray to light-gray, laminated to thin-bedded dolomite and limestone; forms slope, commonly covered with talus; beds distorted from solution of gypsum; 320 feet (98 m) thick.

Ptb **Brady Canyon Member** -- Medium-light-gray to dark-gray, medium- to coarse-grained, thick-bedded, fossiliferous limestone with reddish-brown chert nodules; contains locally common brachiopods, crinoids, and corals; forms prominent cliff; 200 feet (61 m) thick.

Pts **Seligman Member** -- Consists of three parts: upper part is medium-gray, thin-bedded, sandy limestone; middle part is interbedded yellowish-gray, calcareous, very-fine-grained sandstone and grayish-yellow, gypsiferous, calcareous siltstone; and basal part is pale-yellowish-brown, fine-grained sandstone; 115 feet (36 m) thick.

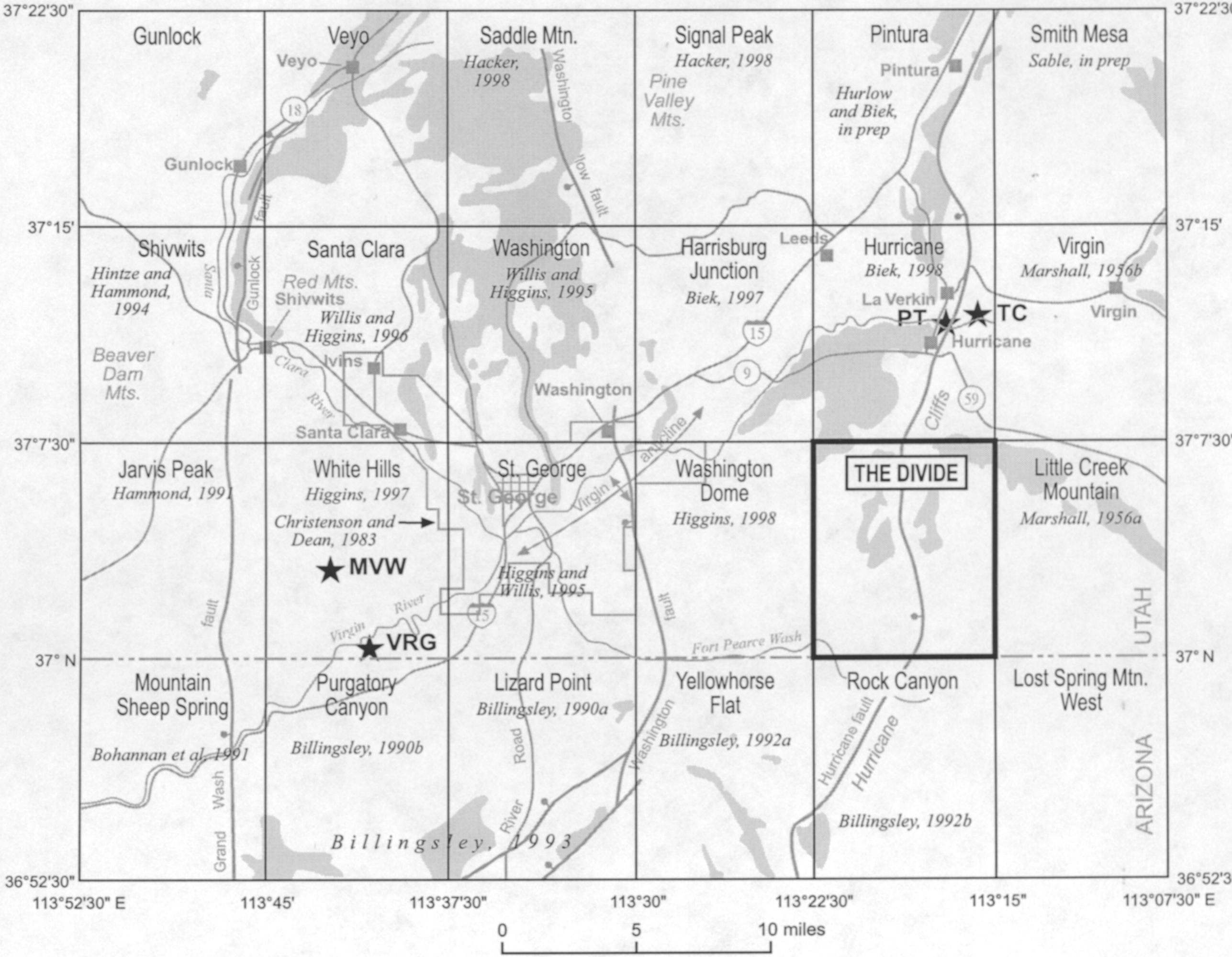
unconformity

Pq **Queantoweap Sandstone** -- Pale-yellow to grayish-pink, calcareous, thick-bedded, fine-grained sandstone; only the upper 75 feet (23 m) is exposed in the quadrangle, but the formation is about 1,300 feet (400 m) thick in the area.

Subsurface Units

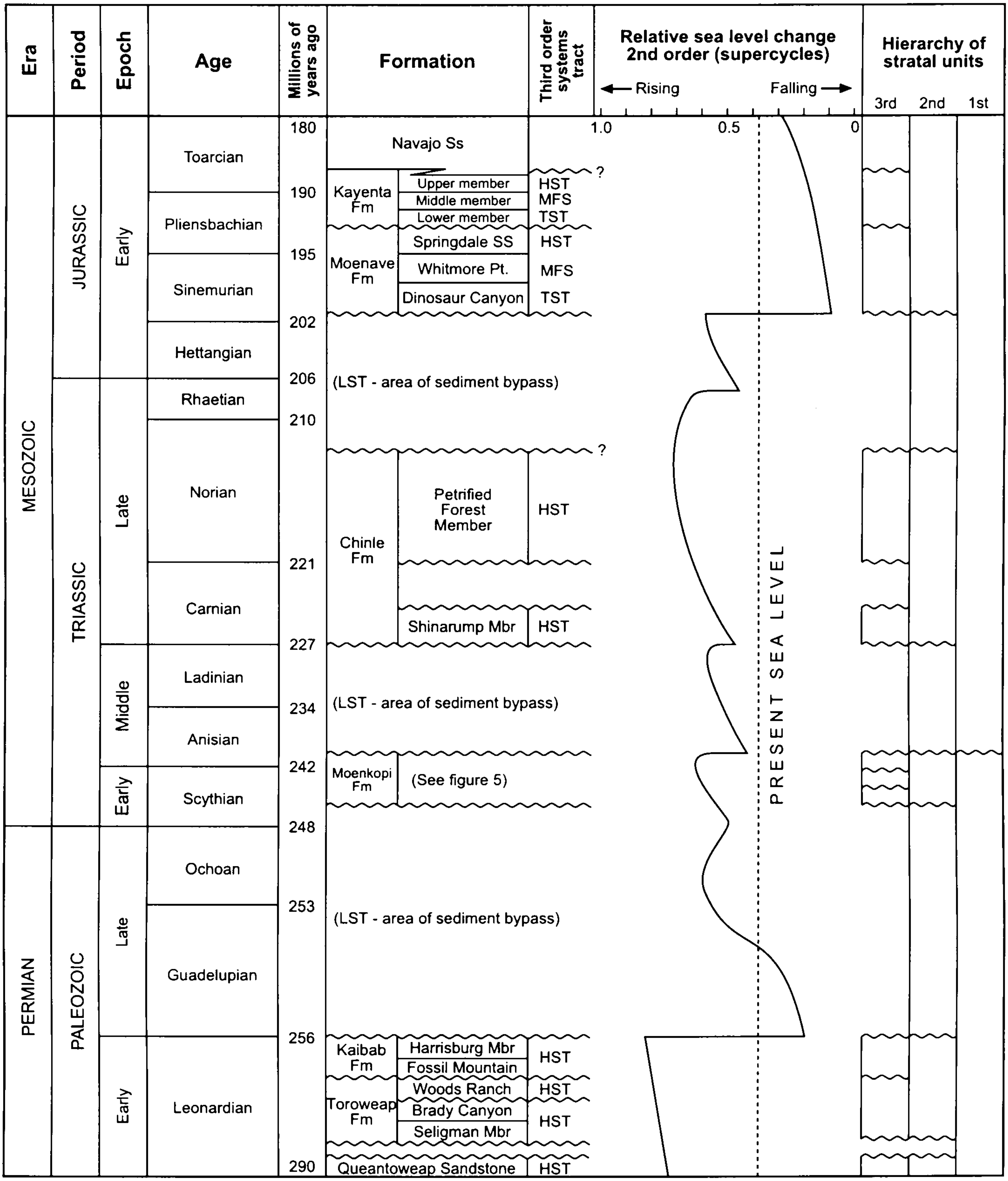
Pzu Paleozoic, undivided — Pre-Queantoweap units shown on cross section only.

Figure 1.



37°22'30"
37°15'
37°7'30"
37° N
36°52'30"
113°52'30" E
113°45'
113°37'30"
113°30"
113°22'30"
113°15"
113°07'30" E
Gunlock
Veyo
Saddle Mtn.
Hacker, 1998
Signal Peak
Hacker, 1998
Pintura
Hurlow and Biek, in prep
Smith Mesa
Sable, in prep
Pine Valley Mts.
Washington fault
Gunlock fault
Shivwits
Hintze and Hammond, 1994
Santa Clara
Red Mts.
Shivwits
Willis and Higgins, 1996
Washington
Willis and Higgins, 1995
Harrisburg Junction
Biek, 1997
Leeds
Hurricane
Biek, 1998
La Verkin
PT
TC
Hurricane
Virgin
Marshall, 1956b
Beaver Dam Mts.
Santa Clara River
Ivins
Santa Clara
Washington
Cliffs
Jarvis Peak
Hammond, 1991
White Hills
Higgins, 1997
Christenson and Dean, 1983
MVW
St. George
Virgin anticline
Washington Dome
Higgins, 1998
THE DIVIDE
Little Creek Mountain
Marshall, 1956a
Higgins and Willis, 1995
Virgin River
VRG
Fort Pearce Wash
fault
UTAH
ARIZONA
Mountain Sheep Spring
Bohannan et al. 1991
Purgatory Canyon
Billingsley, 1990b
Lizard Point
Billingsley, 1990a
Yellowhorse Flat
Billingsley, 1992a
Rock Canyon
Hurricane fault
Hurricane
Billingsley, 1992b
Lost Spring Mtn. West
Grand Wash
River Road
Washington
Billingsley, 1993
0
5
10 miles

Figure 2



HST = highstand systems tract. MFS = maximum flooding stage. TST = transgressive systems tract. LST = lowstand systems tract.

Figure 3.

Figure 4

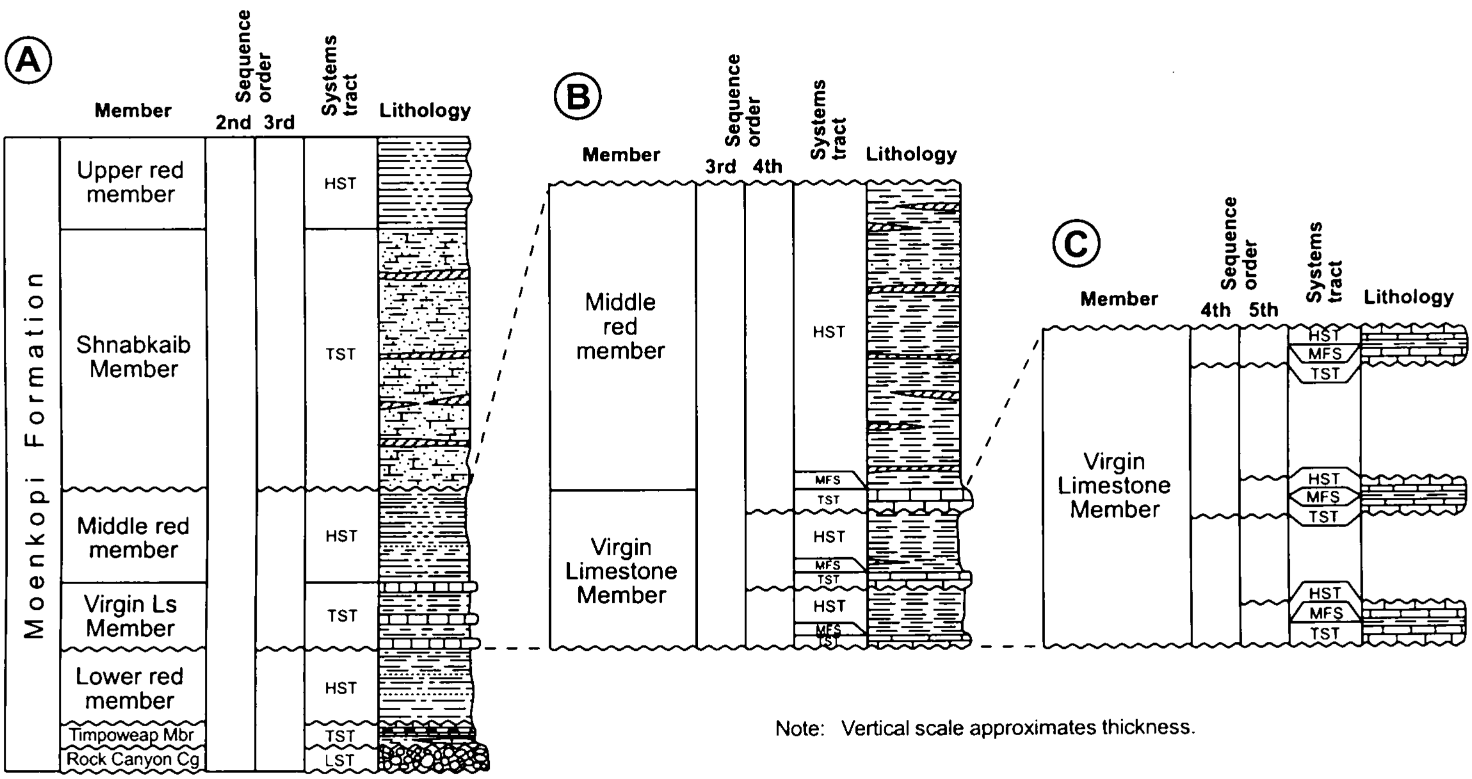


Figure 5.

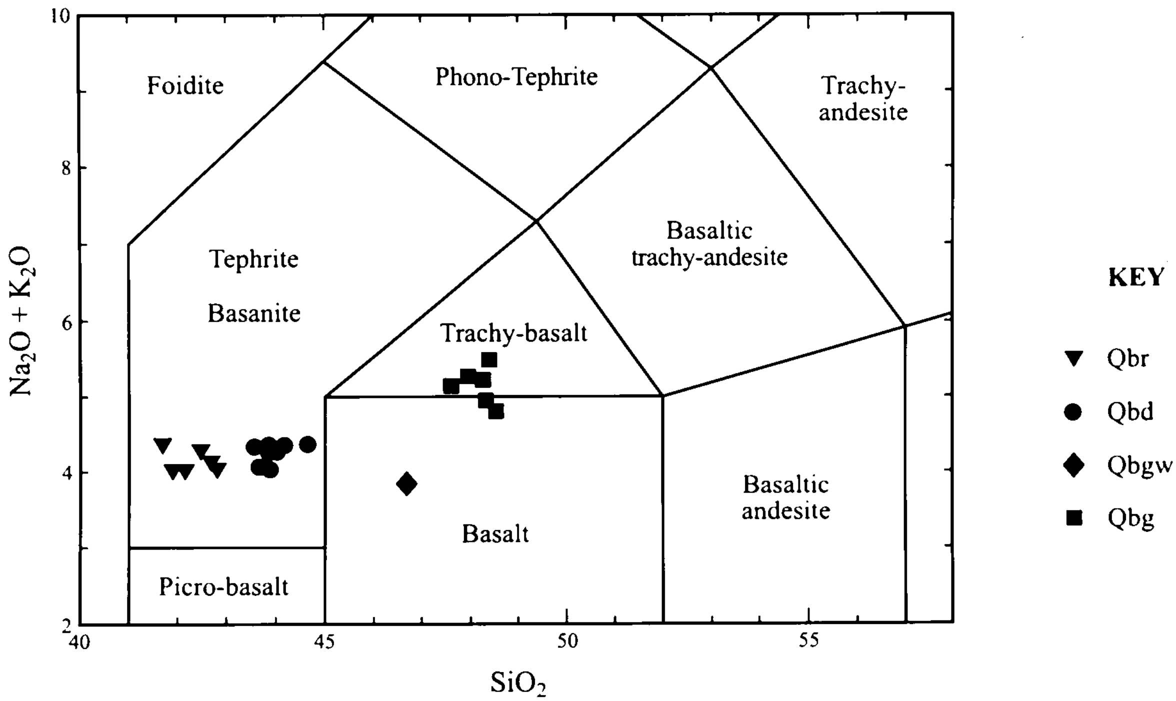

Foidite
Phono-Tephrite
Trachy-
andesite
Tephrite
Basanite
Basaltic
trachy-andesite
Trachy-basalt
Basalt
Basaltic
andesite
Picro-basalt
$Na_2O + K_2O$
SiO_2
10
8
6
4
2
40
45
50
55
KEY
Qbr
Qbd
Qbgw
Qbg

Figure 6.

Figure 7

Figure 8

Figure 9

Figure 10